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Tephrochronology, Petrology, and Stratigraphy of Some Pleistocene Deposits in the Central Plains, Usa.

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TEPHROCHRONOLOGY, PETROLOGY, AND STRATIGRAPHY OF SOME PLEISTOCENE DEPOSITS IN THE CENTRAL PLAINS U.S.A.

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
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in

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by

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TEPHROCHRONOLOGY, PETROLOGY, AND STRATIGRAPHY OF SOME PLEISTOCENE DEPOSITS IN THE CENTRAL PLAINS U.S.A.

John David Boellstorff

ABSTRACT

A simplified method of fission-track dating rhyolitic volcanic glasses has been developed. Eleven deposits of volcanic ash of Pleistocene age from the Central Plains have been dated by means of this technique. The Pearlette Ash (previously assigned late Kansan in age) consists of four significantly different ages of ash--about 0.61 m.y., 0.74 m.y., 1.21 m.y., and 1.97 m.y. The diverse ages of these ash deposits demonstrate some regional correlations are in error.

A new terminology for Pleistocene volcanic ashes in Central Plains is presented. This terminology requires knowledge of the age and the iron, manganese, and samarium content of the ash. This terminology includes both the Pearlette and non-Pearlette ashes.

Ash Name	Age Criterion	Chemical Criteria
Pearlette (restricted)	≃ 0.61 m.y.	≃ 1.1% Fe, 280 ppm Mn, 12 ppm Sm
Hartford	≃ 0.74 m.y.	≃ 1.1% Fe, 280 ppm Mn, 13 ppm Sm
Bishop	≃ 0.82 m.y.	≃ 0.6% Fe, 200 ppm Mn, 5 ppm Sm
Coleridge	≃ 1.21 m.y.	≃ 1.0% Fe, 240 ppm Mn, 11 ppm Sm
Borchers	≃ 1.97 m.y.	≃ 1.2% Fe, 280 ppm Mn, 14 ppm Sm

Heavy minerals and pebble types are useful for correlating tills over a large area. New correlations made with the

aid of these types of data show several generally accepted till correlations may be in error. The new correlations indicate the Nebraskan Till of Shimek (1909) correlates with the upper till (Kansan of Bain, 1896 and Chamberlin, 1896) near Afton, Iowa, rather than the lower till (pre-Kansan). In addition, these correlations indicate Reed and Dreeszen's (1965) Nebraskan sequence in eastern Nebraska is older than the lower till (pre-Kansan or Nebraskan) near Afton, Iowa, and several formally designated till names with separate age assignments have been applied to a single till sheet in Nebraska.

A chronology of early and middle Pleistocene deposits in the Central Plains U.S.A. has been inferred from the till correlations and volcanic ash dates. This chronology indicates that the Nebraskan of eastern Nebraska is older than about 1.2 m.y. and is older than Shimek's (1909) Nebraskan Till and the pre-Kansan or Nebraskan till of the Afton, Iowa, area. The base of the Pleistocene in the Central Plains is at least about 2.0 m.y. old.

A comparison of the inferred chronology for the central Plains with that of the Gulf of Mexico (Beard, 1969) suggests sediments termed Nebraskan in the Gulf of Mexico are older than those termed Nebraskan in the Central Plains.

As they stand, the new correlations and dates on volcanic ashes indicate much of the current terminology used to communicate information about early and medial Pleistocene

events in Nebraska and adjoining areas may not be useful. In addition, the stage names Nebraskan, Aftonian and Kansan need reevaluation and possibly redefinition.

INTRODUCTION

This report is presented in three segments. The first deals with the chronology and chemistry of volcanic ash deposits in Iowa, Kansas, Nebraska and South Dakota. A modified fission-track dating procedure is detailed and applied to eleven volcanic ash deposits. A new terminology based on radiometric dates and chemical compositions is proposed for volcanic ashes previously termed Pearlette.

The second section deals with the petrologic study of glacial tills in eastern Nebraska and adjoining areas. New correlations of tills are made using heavy mineral and pebble type data. Possible ramifications of these correlations are discussed.

The third section integrates the results of the volcanic ash and till studies into a reevaluation of the classification and nomenclature of early and medial Pleistocene deposits in the Central Plains. In addition, a crude chronology for Pleistocene deposits in the Central Plains is proposed and compared with those for the Gulf of Mexico and the Alps.

I THE "PEARLETTE" VOLCANIC ASH PROBLEM

Volcanic ash deposits have been of fundamental importance in the development of the classification of the Pleistocene succession in Iowa, Kansas, Nebraska and South Dakota. Subsequent to the initial recognition of volcanic ash in southwestern Nebraska by Merrill (1885), scores of these deposits have been studied in attempts to determine their stratigraphic position.

In 1886 Todd proposed the volcanic activity that produced the ash was contemporaneous with glaciation in Iowa, Nebraska and the Dakotas. Cragin (1896) named the ash "Pearlette" for the type locality near the old post office at Pearlette, Meade County, Kansas (NW 1/4 sec. 27, T. 30 S, R. 27W) and until recently, the name has been applied to the Pleistocene ash deposits throughout the midcontinent.

As early as 1897 it was recognized that the Pleistocene ash deposits in southwestern Kansas might not all be the same age (Haworth, 1897, p. 257). This possibility was again stated by Smith in 1940 (p. 119). Swineford and Frye (1946) made an extensive study of volcanic ash deposits in southwestern Kansas and concluded the "Pearlette ash" may consist of as many as three ash falls. However, they believed these falls did not differ significantly in age and were mid-Pleistocene. Later, many workers interpreted the "Pearlette" as late Kansan (Yarmouthian) in age (Condra and others, 1947; Frye and others, 1948; Schultz and Tanner, 1957; Miller, 1964). This interpretation became the general concensus of stratigraphers

in the midcontinent and the "Pearlette Ash" was used as a key bed in regional correlation studies and in the development of the classification of the Pleistocene succession of this area.

Recent studies have indicated two or more significantly different ages of Pleistocene ash may occur in the midcontinent (Miller and others, 1964; Reed and Dreeszen, 1965; Izett and others, 1970). Therefore, knowledge concerning the number and relative ages of ash is critical in re-evaluating the framework of the Pleistocene succession here.

Borchardt and others (1972) have shown that three Pleistocene ashes--Green Mountain Reservoir ash, Pearlette-like ash and Bishop ash--can be differentiated by their manganese and samarium content. Izett and others (1970) recognized four Pleistocene ashes by means of petrographic and chemical criteria--Green Mountain Reservoir ash, type-O Pearlette-like ash, Bishop ash, and type-S Pearlette-like ash. The type-O and type-S Pearlette-like ashes had petrographic and chemical characteristics strongly resembling those of Pleistocene rhyolitic ashes from eruptive centers in the Yellowstone National Park area of Wyoming and Idaho. These eruptive centers were hypothesized as the source of the Pearlette-like ashes. Later, based on K-Ar dates on sanidine from the ash at the hypothesized eruptive centers, Izett and others (1971) assigned an age of 1.2 m.y. (million years before present) to the type-S ash and 0.6 m.y. to the type-O ash.

None of the midcontinent ash deposits were dated until Naeser and others (1971) obtained zircon fission-track dates

of about 0.9 m.y. on the ash at the Cudahy Ash Mine and 1.9 ± .02 m.y. on the ash at Borchers Ranch (Fig. 1-1, map nos. 1 and 11, respectively).

A more complete history of the study of the "Pearlette" ash is presented in Appendix C.

I-1 Fission-track Dating of Volcanic Ash Deposits

With the aid of an electron microscope, Silk and Barnes (1959) were the first to observe fission tracks in natural materials. Price and Walker (1962) presented a chemical etching technique which enlarges the fission tracks making them visible with an optical microscope.

The most likely cause of fission tracks in natural terrestial materials is the spontaneous fission of U^{238} (Price and Walker, 1963). Spontaneous fission also occurs in U^{235} and Th^{232}, but their spontaneous fission yield is far less than that of U^{238} (Durrani and Khan, 1970, p. 437). Therefore, in most cases, the contribution of fission tracks from U^{235} and Th^{232} is negligible.

Fleischer and others (1965a) proposed an "ion explosion spike" model for the formation of fission fragment damage trails or tracks. According to this model the passage of a massively charged fission fragment ionizes atoms adjacent to its trajectory. The damage trail or track is produced by mutual repulsion of these ions outward from the trajectory into the surrounding structure.

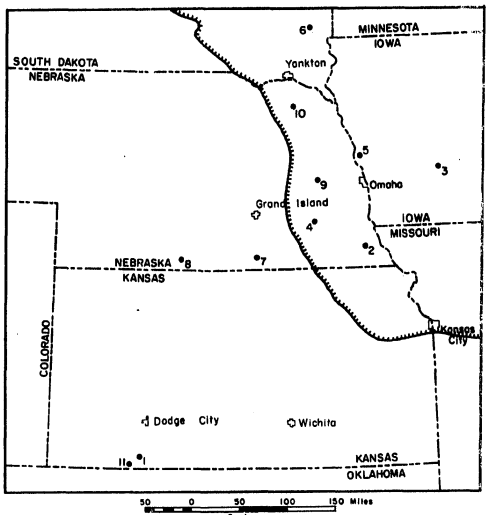

Figure 1-1. Generalized location of volcanic ash sample sites. For specific location see Table 1. Hatchured line approximates maximum extent of continental glaciation in the study area (hatchures on glacier side).

Fleischer and Price (1964a) outlined the basic theory and technique for fission-track dating glasses. Fundamentally, their technique consists of determining the ratio of the density of spontaneous fission tracks (those caused by the spontaneous fission of U^{238}) to the density of tracks caused by the induced fission of U^{235} by thermal neutrons (low energy) in a nuclear reactor.

The density of spontaneous tracks (ρ_s) was determined by polishing the glass to an optical finish and then etching it with hydrofluoric acid (HF) to enlarge the tracks and make them visible with an optical microscope. Then the sample was scanned at 250-500 magnification and the number of tracks in a measured area counted. Next, the sample was subjected to a measured dose of thermal neutrons, repolished, re-etched, and the total density of fission tracks determined. The total track density minus the density of spontaneous tracks, determined earlier, yields the induced track density (ρ_i). Fleischer and Price (1964b) showed the age in years (A) of the sample is a function of the ratio ρ_s/ρ_i and the neutron dose (ϕ) as shown below:

$$\rho_s/\rho_i = [\exp(\lambda_D A) - 1]\frac{\lambda_F}{\lambda\phi\sigma} \qquad \text{equation 1}$$

where: λ_F = spontaneous fission decay constant of U^{238}--$6.85 \times 10^{-17}\ yr^{-1}$ (Fleischer and Price, 1964c)

λ_D = Total decay constant of uranium--$1.54 \times 10^{-10}\ yr^{-1}$

σ[1] = Cross section for thermal neutron induced fission of U^{235}--$580 \times^{-24}\ cm^2$

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[1]These values are taken from the Chart of the Nuclides 1966, Knolls Atomic Power Laboratory.

I^1 = Isotopic ratio U^{235}/U^{238}--7.25×10^{-3}

With substitution of these values equation 1 can be reduced to:

$$A = 14.95 \times 10^9 \log [1 + (9.50 \times 10^{-18}) (\phi) (\frac{\rho_s}{\rho_i})] \quad \text{equation 2}$$

Theoretically the age obtained can be considered calendar years. Evidence indicating that fission-track years are roughly equivalent to calendar years was demonstrated by showing that the fission-track age of man-made glasses was nearly concordant with their year of manufacture (Brill and others, 1964). However, as with other "radiometric" dating techniques, uncertainties in the knowledge of the physical "constants" and the history of the sample in addition to inaccuracies in the measurement of variables necessitates caution in the interpretation of the measured dates as calendar years.

Fleischer and others (1965) dated glass shards from Olduvai Gorge, Tanganyika, by using a fission-track technique that employed the conventional method for particulate materials--i.e. mounting in a rigid medium, polishing, and scanning the same shards in determining ρ_s and ρ_i.

Contemporaneous with and independent of the development of the dating technique presented in this paper, Macdougall (1971) dated volcanic glass shards from marine sediments. His technique followed that above except, as in my technique, separate aliquots of sample were used in determining ρ_s and ρ_i.

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[1]These values are taken from the Chart of the Nuclides 1966, Knolls Atomic Power Laboratory.

Initially I attempted to date shards by using the conventional method for particulate materials, but I found it impossible to get the thin, platy shards to lie flat in the mounting mediums (Duco cement and casting plastic). Even sprinkling the shards on a flat surface and then adding the medium or centrifuging a plastic-ash slurry failed. Most of the shards were content to stand on edge. Consequently, the polished surfaces obtained were too small to make reliable track counts practical. Because of this problem, I decided to modify the fission-track dating technique so a rigid mount of the shards would not be necessary.

The lack of a rigid mount made it impossible to polish the shards or to scan the same shards in determining ρ_s and ρ_i. However, the lack of an optical polish on the shards presented no difficulty in identifying fission tracks having sharp bottoms and a long axis greater than two microns.

Theoretical factors considered in this study

The use of different groups of shards in determining the spontaneous and induced track densities requires that both past and present uranium distributions be homogeneous and migration of elemental uranium has not occurred.

The past distribution of uranium is represented by spontaneous fission tracks and the present distribution by induced fission tracks. These distributions were examined from fission-track density data obtained while determining the ages of three subsamples from each ash deposit. The

basic data for each of the three subsamples was three measurements of the number of spontaneous tracks per 100 unit areas on non-irradiated shards and four measurements of the number of induced plus spontaneous tracks per 25 unit areas on irradiated shards.

The homogeneity of the past and present uranium distributions and the possibility of uranium migration were analyzed statistically using data obtained while dating the Dam 7 ash (Fig. 1-1, loc. no. 4). In order to examine the possibility of uranium migration, three age determinations were made on each of the three subsamples--one after 110-second etch, a second after a 120-second etch, and a third after a 130-second etch. Thus, in effect, I was looking at both the past and present uranium distributions at three successively deeper levels within the shards--about 11, 12, and 13 microns deep. The spontaneous and induced track denisty measurements from the nine age determinations were separately treated statistically by means of a randomized block design nested analysis of variance scheme (see Appendix D). Within each level, no significant difference in the number of spontaneous tracks per 100 areas was detected. Therefore, I concluded both the past and present distributions of uranium were homogeneous within each level. In addition, no significant difference in the number of spontaneous tracks per 100 areas was detected between levels. Because the density of spontaneous fission tracks is an indicator of the uranium concentration from the time of formation of the glass to the present, and because no

significant difference was detected in the spontaneous track density at the three levels, I concluded migration of uranium had not occurred in the Dam 7 ash.

Data concerning the homogeneity of uranium in the ash from other localities was not analyzed statistically because they appeared to be as uniform as those for the Dam 7 ash. Data concerning the migration of uranium were not obtained from the other ash localities. Because all of the ashes are nearly alike in bulk composition (Izett and others, 1970) and lack of alteration, I assume uranium migration had not occurred in any of the ashes.

Contamination is a factor that must be considered with any dating technique. Surface uranium contamination on the shards will form fission tracks. The maxium depth these fission tracks penetrate into the shards can be found by measuring the effective range (R), the mean length over which a fission fragment path may be revealed by etching. A method used for evaluating R is to make measurements of the projected length of those tracks most nearly parallel to the etched surface (Fleischer and Price, 1964a). Numerous such measurements indicated a value of about 12 microns for R. Thus, in order to remove the fission tracks due to surface uranium contamination, a 12-micron rind of glass must be etched away.

To determine the minimum etching time (T) needed to remove a 12-micron thick rind of glass, it is necessary to know the general etch rate (G) of the shards. The general

etch rate is the rate at which the glass as a whole etches (the minute portion of the glass damaged by fission fragments dissolves at a faster rate than the glass as a whole and thus the tracks are enlarged). G was measured on ash shards from three localities (Fig. 1-1, locs. no. 4,6 and 10) and on glass plates fused from ash from location 4. These measurements yielded a value of 6.2 ± 0.3 microns per minute in continuously agitated 24 percent HF at 23° C. This value for G and these etching conditions were used throughout the dating work because the bulk chemistry of the Pleistocene ashes in the midcontinent is similar (Izett and others, 1970, and Borchardt and others, 1972). Using the relationship GT = R, T was determined to be about 116 seconds.

When etched as outlined above, the shard surface on which the fission tracks are counted should be devoid of fission tracks due to contamination. Moreover, it is an internal surface--i.e. the fission tracks crossing the counting surface originated from fissions occurring within the total effective range of fission tracks in the glass--both above and below the counting surface. In this respect, the technique presented here differs from those employing a polished and etched rigid mount. The counting surface obtained with a polished rigid mount ranges from internal to nearly external and fission tracks due to contamination may not be completely eliminated.

Fleischer and Price (1964b) indicated the age equation is valid only if both ρ_s and ρ_i are determined on the same

internal surface. They pointed out that a correction must be applied to the equation if the surface of the material being dated dissolves at an appreciable rate so that new tracks are exposed during the etch period. Even though the volcanic ash shards do dissolve at an appreciable rate, no correction in the equation is necessary when using the dating technique presented here because (i) separate aliquots of shards are used in determining ρ_s and ρ_i, (ii) both aliquots are given identical etching treatments, (iii) the effects of contamination are removed and an internal surface is achieved, and (iv) the distribution or uranium is homogeneous. Thus, in effect, both ρ_s and ρ_i are determined on the same internal surface.

Dating the ashes

Ash samples were collected from the purest part of the eleven ash deposits studied (Fig. 1-1 and Table 1-1). They were then air dried and coarser fraction separated by sieving. This fraction was cleaned in an ultrasonic bath by means of repeated washing with .01 N sodium oxalate solution ($Na_2C_2O_4$) followed by wet-sieving over a U.S. Standard 100-mesh sieve (the 200-mesh sieve in the case of the fine-grained ashes) to remove the finer particles. The samples were than rinsed with distilled water, next by acetone, and oven dried at 63° C for 1 hour. Each sample was split into three subsamples which were further split into paired portions and placed into separate 2-dram plastic vials marked 1, 1'; 2, 2'; ...33, 33'.

All of the prime-numbered portions were irradiated at the same time in the graphite section of the Georgia Institute of Technology Research Reactor. Because a ±20 percent vertical flux gradient was reported to be present in the irradiation chamber (written communication, Dr. Milton McLain, Jr.) the 33 subsamples were placed in three layers, with one subsample from each locality per layer. Several pieces of a standard dosimeter glass for measuring the neutron dose were included with each layer (the dosimeter glass was generously donated by Dr. R. L. Fleischer).

After irradiation, the neutron dose sustained by each of the three layers of samples was determined following the technique of Fleischer and others (1965b). This technique requires etching a standard glass and determining the density of induced fission tracks per cm^2 (ρ). The neutron dose (ϕ) can then be obtained from the relationship:

$$\phi = 2.61 \times 10^{11} \rho \pm 15\% \qquad \text{equation 3}$$

I employed two methods of treating the standard glasses prior to determing ρ. The first (Fleischer and others, (1965b) requires grinding and polishing the glass to obtain an internal surface, then etching this surface for 2 to 10 seconds in 48 percent HF. The second method (Reimer and others, 1970) requires only that an unpolished external glass surface be etched for 7 seconds or more in 48 percent HF to obtain an internal surface on which to determine the induced track density. I etched the external surface for 10 seconds in order to be certain of having an internal surface.

The average values for the neutron dose obtained using the two etching methods differed. A value of 1.47 ± 0.11 X 10^{14} neutrons/cm^2 was obtained using the method of Fleischer and others (1965) and a value of 1.76 ± 0.07 X 10^{14} neutrons/cm^2 was obtained using the method of Reimer and others (1970).

The lower dose values obtained using Fleischer and others (1965) etching technique led me to believe the grinding and polishing process may have caused annealing in the glass, and consequently, a lower track density. Therefore, the higher dose values obtained using Reimer and others (1970) etching technique were used in the initial age calculations.

In a subsequent experiment, gold flux wires were included along with the standard glass in order to obtain an independent measurement of the dose.[2] As shown below, dose values obtained using the flux wires agreed with the dose values obtained from standard glasses etched following Fleischer and others (1965) technique.

The error in thermal neutron dose measurement associated with gold flux wires is no greater than 6% (personal communication, Dr. Edgar Steele). Because the dose values obtained using the gold flux wires and the standard glass (5-second etch) were nearly the same, the 15% possible error associated with the glass standard equation may be too high.

Because of this experiment, the ages of the volcanic ash deposits were recalculated using the neutron dose values obtained

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[2]The dose measurements on the flux wires were made by personnel at the Georgis Institute of Technology Research Reactor.

Irradiation #	Measured Dose[a]		
	Standard Glass		Gold Flux Wires
	Fleischer and others technique	Reimer and others technique	
1	1.44 ± 0.08	1.79 ± 0.16	1.31 ± 0.22
2	1.32 ± 0.06	1.56 ± 0.06	1.28 ± 0.20
3	1.34 ± 0.16	1.75 ± 0.23	1.43 ± 0.19
	1.37 ± 0.06	1.70 ± 0.12	1.34 ± 0.08

[a]Values are times 10^{14} neutrons/cm^2

using the etching technique of Fleischer and others (1965). As stated earlier, the average of these values is 1.47 ± 0.11 X 10^{14} neutrons/cm^2.

For each age determination, separate cubic centimeter (cc) samples of irradiated ash and its non-irradiated counterpart are successively etched and the fission tracks counted the same day. Even though an etching period of about 116 seconds was found to be sufficient for obtaining an internal surface, the ash usually was etched for 130 seconds to be certain of this. However, some finer-grained samples were etched only 120 to 125 seconds because after 130 seconds all shards were destroyed. In all cases, the samples were etched in 30 ml of 24 percent HF at 23° C and agitated continuously throughout the etch period. Etching action was stopped by flooding the sample with 200 ml of water. Twenty seconds later the solution was decanted. The residual shards were repeatedly rinsed with distilled water until the supernatant liquid registered neutral on litmus paper. In order to procure enough etched shards for dating the fine-grained ashes, several 1cc portions had be

etched.

The etched shards were placed on a glass slide, a few drops of water added, and a cover slip placed over them. This mount was then scanned at 500 magnification in transmitted light and a Leitz Ortholux microscope. A mechanical state with the N-S axis set at 0.2 mm was used to avoid overlap between E-W sweeps. When a shard filled the area outlined by a circular eyepiece reticle, tracks within the outlined area were counted. Only those tracks having a sharp bottom and an axis at least 4 microns long were counted. These identification criteria minimized counting errors because tracks this large are easily distinguished from natural porosity and from adhering dust particles and are not likely to be overlooked (Fig. 1-2). Normally, to facilitate the scanning, only flat shards without ribs were examined. Both flat shards and those with single ribs had to be examined in dating some of the more pumiceous ashes.

The density of spontaneous tracks (ρ_s) is merely the total density of tracks on the nonirradiated shards. The density of induced tracks (ρ_i) is the total density of tracks on the irradiated shards minus the total density of tracks on the nonirradiated shards. The spontaneous track density is a measure of the amount of uranium that has decayed and the induced track density, along with the neutron dose (ϕ) is a measure of the amount of uranium still present. The age of the sample is then determined using equation 2 and the values for ρ_s, ρ_i, and ϕ.

Figure 1-2. Induced fission tracks in a shard from the Borchers Ranch ash locality (Figure 1, location 11). Arrows point to fission tracks.

By means of the dating technique outlined above fission tracks on both sides of the etched shards are revealed and counted. Thus, the densities observed under the microscope are apparent densities and are twice the true densities. However, as the calculated age is dependent only on the ratio ρ_s/ρ_i (see equation 2) either the apparent densities or the true densities can be used for calculating the age of the sample. Because tracks on both sides of the etched shards are revealed, the time required to count a given number of tracks is one-half of the needed if tracks on only one side of the shards were revealed.

An example of an age calculation is presented below using equation 2 and the data for sub-sample number 44 (see Table 1-1).

$$A = 14.95 \times 10^9 \log \{1 + (9.5 \times 10^{-18})(\frac{\rho_s}{\rho_i})(\phi)\} \quad \text{equation 2}$$

where:

ρ_s = spontaneous track density = 2,037/cm^2
ρ_i = induced track density = 31,747/cm^2
ϕ = neutron dose = 1.42 X 10^{14}/cm^2
A = age of the sample in years

With this data, equation 2 becomes;

$$A = 14.95 \times 10^9 \log [1 + (9.5 \times 10^{-18}) (\frac{2,037}{31,747})(1.42 \times 10^{14})]$$

$$= 14.95 \times 10^9 \log [1 + 0.00008656]$$

log of 1.0000856 = 0.00003759.

Then, solving equation 2 for A, the result is

$$A = (14.95 \times 10^9)(3.759 \times 10^{-5})$$

$$= 56.1971 \times 10^4 \text{ years}$$

$$= 0.562 \text{ m.y.}$$

As discussed earlier, in the course of each age determination, several measurements of the density of spontaneous and induced tracks were made in order to examine the homogeneity of uranium in the samples. Usually about 100 spontaneous tracks and about 500 induced tracks were counted in making each age determination. In the case of the fine-grained ashes the number of tracks counted was smaller because nearly all of the shards were destroyed by etching. Each age determination required approximately 3 to 5 hours of microscope work.

Dating results and discussion

My dates of 0.64 ± 0.07 m.y. for the ash from the Cudahy Ash Mine and 1.97 ± 0.25 m.y. for the ash at Borchers Ranch (Table 1-1, loc. nos. 1 and 11) are in approximate agreement with the zircon fission-track dates of 0.9 m.y. and 1.9 ± o.2 m.y. respectively obtained by Naeser and others (1971) on these same ashes. They considered their date of 0.9 m.y. for the ash at the Cudahy Ash Mine a maximum.

A fission-track date of 0.82 ± 0.16 m.y. was obtained for the ash in Nuckolls County, Nebraska, which has been chemically correlated with the Bishop Tuff of California (Izett and others, 1970). This date lies in between K-Ar dates for the Bishop Tuff of California -- 0.95 m.y. (Evernden and others, 1964) and 0.7 m.y. (Dalrymple and others, 1965).

Table 1-1: Fission-Track Data and Ages of Some Midcontinent Pleistocene Volcanic Ash Deposits.

Map	Location	Stick[a] Tier (cm)	Subsample No.	Spontaneous Tracks		Induced Tracks		Rem[b]	Fission-track age ($\alpha_{\gamma,\gamma}$)[c]		
				Tracks counted	Apparent[d] Density/cm²	Tracks counted	Apparent[d] Density/cm²		Subsample	Sample	Group
1	SW 1/4 sec. 2, T. 31 S., R. 39 W., Meade County, Kans. (Cudahy Ash Bed)	130	4a	108	2,037	361	31,747	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.362 0.497 0.454	0.44 ± .07	
		130	4b	113	2,132	496	27,955				
2	SW 1/4 SE 1/4 sec. 26, T. 6 N., R. 11 E., Johnson County, Kans. (Elk Creek Ash Bed)	130	8	101	1,905	493	27,899	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.598 0.570 0.557	0.57 ± .02	
		130	9	104	1,962	500	28,454				
		130	10	99	1,867	512	28,971				
3	SE 1/4 sec. 8, T. 78 N., R. 19 W., Cedaria County, Iowa (unnamed locality)	130	22	118	2,226	565	31,690	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.455 0.631 0.533	0.59 ± .05	Pearlette ash (reworked) 0.61 ± .04
		130	23	120	2,264	634	35,623				
		130	24	119	2,245	638	36,106				
4	C. sec. 36, T. 9 E., R. 2 E., Bennett County, Nebr. (Ben T or Bennett Ranch Site)	130	1a	101	1,479	417	23,588	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.530 0.682 0.705		
		130	1b	100	1,986	428	24,220				
		130	1c	108	1,847	448	25,426				
		130	2a	113	1,917	438	24,853	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.546 0.702 0.722	0.64 ± .07	
		130	2b	108	1,837	437	24,910				
		130	2c	108	1,707	313	17,831				
		130	3a	97	1,652	493	29,599	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.463 0.596 0.644		
		130	3b	93	1,754	467	25,296				
		130	3c	116	2,150	506	28,635				
5	NW 1/4 NE 1/4 sec. 5, T. 81 N., R. 44 W., Harrison County, Iowa (County Line Section, or Little Sioux Site)	130	18a	94	1,773	381	21,561	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.720 0.771 0.718 0.718 0.836 0.715	0.71 ± .04	
		130	18b	112	2,113	434	23,994				
		130	19a	110	1,975	504	28,521				
		130	19b	108	2,037	495	28,012				
		130	20a	112	2,113	505	28,579				
		130	20b	122	2,301	481	27,220				
6	NW 1/4 NW 1/4 sec. 11, T. 108 N., R. 53 W., Hamilton County, N. Dak. (Nortest Site)	130	4a	161	2,860	466	26,371	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.885 0.730 0.810 0.775 0.731 0.818	0.76 ± .09	Nortest ash 0.76 ± .06
		130	4b	141	2,660	549	31,060				
		130	5a	106	1,952	430	23,796				
		130	5b	138	2,563	381	21,574				
		130	6a	108	2,037	472	25,981				
		130	6b	129	2,433	396	23,728				
7	SE 1/4 sec. 36, T. 3 N., R. 8 W., Nuckolls County, Nebr. (unnamed locality)	125	41	43	1,625	159	20,190	1.42 ± .32 1.40 ± .19 1.39 ± .12	0.791 0.986 0.670	0.82 ± .16	Bishop ash 0.82 ± .16
		125	42	64	1,905	218	27,751				
		125	43	52	2,207	222	28,381				
8	SW 1/4 NE 1/4 sec. 11, T. 2 S., R. 38 W., Sherman County, Nebr. (Type Locality of the Loper Formation)	130	32	47	5,983	253	32,287	1.42 ± .32 1.40 ± .19 1.39 ± .12	1.430 1.298 0.857	1.36 ± .40	
		130	33	40	6,158	353	46,465				
		130	34	21	5,347	108	34,739				
9	NE sec. sec. 32, T. 13 S., R. 1 E., Butler County, Nebr. (Devil City Locality Two Beds)	125	29	158	3,729	362	44,083	1.42 ± .32 1.40 ± .19 1.39 ± .12	1.489 1.301 1.008	1.16 ± .20	Columbian ash 1.21 ± .05
		125	30	132	4,450	302	46,285				
		125	31	134	5,888	380	48,574				
10	NW 1/4 NE 1/4 NE 1/4 sec. 11, T. 39 N., R. 1 E., Cedar County, Nebr. (Columbian Ash Site)	130	12	93	5,432	373	45,430	1.42 ± .32 1.40 ± .19 1.39 ± .12	1.086 1.425 1.186	1.22 ± .17	
		130	13	102	4,962	573	34,726				
		130	14	101	4,893	596	35,973				
11	NW 1/4 NE 1/4 sec. 21, T. 33 S., R. 38 W., Meade County, Kans. (Southern Ranch-Type Locality of Meade and Crooked Creek Formations)	130	26a	113	6,338	547	30,655	1.42 ± .32 1.42 ± .32 1.40 ± .19 1.40 ± .19 1.39 ± .12 1.39 ± .12	1.791 1.862 1.781 2.274 1.296 1.797	1.97 ± .25	Northern ash 1.97 ± .25
		130	26b	115	6,328	561	30,615				
		130	27a	111	6,281	611	34,883				
		130	27b	124	7,017	538	30,445				
		130	28a	128	7,164	478	27,050				
		130	28b	104	5,885	488	28,069				

a. Shards were etched in 24% HF at 45° C.
b. I 10^{14} neutrons/cm^2.
c. Ages calculated using $\lambda_f = 6.85 \times 10^{-17}$ yr^{-1}. The ± value presented for each sample and group is standard deviation of the age determinations for the subsamples and samples respectively. These values do not include a possible 15% error in the measurement of the neutron dose (ϕ) using glass standards ($\phi = 2.61g \times 10^{14} \pm 15\%$ neutrons/cm^2).
d. The apparent density is twice the true density because fission-track on both sides of the shards are visible and counted.

Statistical treatment of the age data[3] was performed using randomized block-design analysis of variance schemes supplemented by Duncan's multiple range test, paired t-tests and least significant difference (L.S.D.) tests (see Appendix E).

The application of these statistical tests required making the assumption that the variation in age within an ash lentil is no greater than the variation in age measured in the bulk sample. This assumption seems reasonable because these deposits are of very limited extent (generally only several acres) and consist of virtually unaltered volcanic glass. There is no evidence indicating that the individual ash lentils accumulated over a long period of time. At each of the localities sampled the ash is very pure at the base and becomes silty towards the top. This silty portion may represent ash and silt washed into depressions from the adjacent land surface and/or later reworking of the upper parts of the ash deposit. The assumption appears to be reasonable considering statistical analyses of the dates for the ashes from localities 1 through 6 indicate age differences between samples had to exceed about 0.1 m.y. (L.S.D. value 0.097 m.y.) in order to be statistically significant.[4] Thus, for the above assumption

[3]For these analyses the data consisted of the average age of each of the three subsamples for each locality.

[4]Because the ashes at localities 1 through 6 were similar in age and chemically alike, statistical analyses of these dates were needed to determine if two or more significantly different ages of ash were represented among these six ashes.

to be false would require either the ash to have formed and accumulated over a period of time greater than about 0.1 m.y. or that some process differentially affected the measured age of an ash lentil deposited at a "point" in time. The purity of the basal portion of the ash, the freshness of the glass, and the small size of the lentils indicate neither of these alternatives is plausible.

Results of the statistical analyses indicate four significantly different ages of ash are represented among the eleven ash deposits dated (see Table 1-1). Even though the statistical analyses indicate that Hartford ash and the Bishop ash are not significantly different in age, chemical analyses (to be discussed later) show these ashes are distinct.

In a subsequent experiment the validity of the assumption that the age variation within an ash lentil is no greater than the age variation in the bulk sample was examined by resampling and redating the ash at the County Line Section, Iowa (Fig. 1-1, loc. no. 5). Three ash samples were collected from the basal part of the ash layer with the samples being taken about 200 feet apart. The samples were treated as outlined earlier (see "Dating the Ashes"). Two age determinations were made on each sample. The dose values used were those determined using Fleischer and others (1965) etching technique.

In order to examine the validity of the assumption it was necessary to make direct comparisons of the dates on the three samples of the ash from the County Line Section with the

dates obtained earlier on a single sample of this ash. Making such comparisons required that the new dates be standardized with those obtained earlier. Standardization was performed by including and redating three splits from the original sample of the ash from Borchers Ranch along with the new samples of the ash from the County Line Section. The ash from Borchers Ranch was chosen for the standard because of the concordant dates obtained by two different methods--1.97 ± 0.25 m.y. (fission-track on glass, this study) and 1.9 ± 0.2 m.y. (fission-track on zircon, Naeser and others, 1971).

As shown on Table 1-2 the new date on the ash from Borchers Ranch was 1.77 ± 0.29 m.y. as compared to 1.97 ± 0.25 m.y. obtained earlier. Therefore, in order to directly compare the new dates for the three samples of the ash at the County Line Section with those obtained earlier on a single sample from this ash, it was necessary to multiply the measured dates by

$$\frac{\text{1.97 (original date on ash sample from Borchers Ranch)}}{\text{1.77 (new date on same ash sample from Borchers Ranch)}} = 1.11299.$$

The standardized date of 0.714 ± 0.048 m.y. for the three new samples of ash from the County Line Section are in excellent agreement with the earlier date of 0.71 ± 0.04 m.y. (see Table 1-2) obtained on three splits from a single sample of this ash. The range of standardized dates for the six age determinations made on the three new samples was 0.110 m.y. as compared to a range of dates of 0.137 m.y. for the six age determinations made on the single sample dated earlier. In addition, the dates of the three new samples of ash at the

Table 1-2: Data for Examining the Age Variation Within the Ash Lentil at the County Line Section, Iowa.

Location	Sample No.	Spontaneous Tracks		Induced Tracks		Dose[a]	Fission-track age (m.y.)		
		Number Counted	Apparent[b] Density/cm^2	Number Counted	Apparent Density/cm^2		Measured		Normalized[c]
							Subsample	Subsample[d]	Sample
County Line Section, Iowa	1-9a	92	2499	415	33,844	1.34 ± 0.16	0.610	0.678	0.688 ± 0.014
	1-9a	91	2472	400	32,567	1.34 ± 0.16	0.627	0.698	
	1-9b	101	2743	441	35,990	1.32 ± 0.06	0.614	0.683	0.680 ± 0.004
	1-9b	100	2716	446	36,316	1.32 ± 0.06	0.608	0.677	
	1-9c	81	2200	350	28,520	1.44 ± 0.08	0.685	0.762	0.775 ± 0.018
	1-9c	92	2499	385	31,372	1.44 ± 0.08	0.707	0.787	
							(0.642 ± 0.043)	(0.714 ± 0.048)	
	Subsample No.								
Borchers Ranch, Kansas	1-7a	108	7040	447	36,311	1.34 ± 0.16	1.602		
	1-7a	113	6139	458	37,293	1.34 ± 0.16	1.360		
	1-7b	112	7301	402	32,790	1.32 ± 0.06	1.813		
	1-7b	101	6584	395	31,878	1.32 ± 0.06	1.681		
	1-7c	114	6193	352	28,683	1.44 ± 0.08	1.917		
	1-7c	126	6845	336	27,379	1.44 ± 0.08	2.220		
							(1.766 ± 0.293)		

a. X 10^{14} neutrons/cm^2

b. The apparent density is twice the true density because fission-track on both sides of the shards are visible and counted.

c. The measured dates for the ash at the County Line Section, Iowa, were normalized by redating the ash sample from Borchers Ranch, Kansas, at the same time. Because the average date for the Borchers ash was 1.97 in the original experiment (See Table 1-1), it was necessary to multiply the new dates for the resampled ash at the County Line Section, Iowa by $\frac{1.97}{1.77}$ = 1.11299 in order to directly compare the dates on the three new samples with the dates on the original sample of the ash at the County Line Section.

d. The dates measured on the original single sample of the ash from the County Line Section were: 0.771, 0.725, 0.720, 0.718, 0.718 and 0.634 m.y. (from Table 1-1).

County Line Section are within 0.095 m.y. of each other--within the limit of nonsignificance (L.S.D. of 0.097 m.y.) determined earlier by statistical analysis of the age data for ashes from localities 1 through 6. These results indicate the age variation between the 3 new samples of ash from the County Line Section is no larger than the age variation measured earlier (see Table 1-1, loc. no. 5) within a single sample of this ash. Therefore, I conclude the assumption that age variation within an ash lentil is no larger than that within a bulk sample of that ash to be valid.

The possibility of resetting the radiometric "clock" must be considered when interpreting the dates obtained with any absolute dating technique. With the fission-track technique this can occur by means of annealing or losing apontaneous tracks (Storzer and Wagner, 1969). Loss of these tracks can be caused by a brief high-temperature event, a lengthy low-temperature history (even at ambient temperature), or by a high pressure event (oral communication, R. L. Fleischer). If a loss of spontaneous tracks has occurred, the measured age will be too young.

While performing laboratory annealing experiments Storzer and Wagner (1969) found the diameter of fission tracks decreases concurrently with the track density. They concluded the measured fission track age is valid only if the mean diameter of the spontaneous tracks is nearly identical with that of the induced tracks. They presented a technique for the construction of a calibration curve which would allow

one to correct the lowered age obtained from a thermally affected sample. By determining the ratio of the mean diameter of the spontaneous tracks to the mean diameter of the induced tracks in the sample, the percent track density lost can be read from the calibration curve and a correction applied to the measured age.

Measurements of spontaneous and induced track diameters on ash shards from the Cudahy Ash Mine, Kansas; from Hartford, South Dakota; from Coleridge, Nebraska; and from Borchers Ranch, Kansas (Fig. 1-1 and Table 1-1, loc. nos. 1, 6, 10, and 11, respectively) showed the mean diameter of spontaneous tracks in each of these ashes to be about 15 percent smaller than the mean diameter of induced tracks. The diameter of the spontaneous tracks has not only been reduced, but it has been reduced to about the same degree in ashes having a measured age ranging from about 0.61 m.y. to 1.97 m.y. and distributed over a broad geographic area! Initially, I thought oven-drying the samples at 63^{o} C during the clean-up process was responsible for the decrease in spontaneous track diameter. Therefore, spontaneous track diameters were measured on fresh samples which had been subjected to air drying only. Because these measurements were virtually the same as those made on the oven-dried samples I concluded the reduction in the mean diameter of spontaneous tracks was not induced by oven drying.

Calibration curves for tektites (Storzer and Wagner,

1969 and 1971), which have compositions somewhat similar to those of the volcanic ashes dated, indicate the dates presented in Table 1-1 would have to be increased at least 20 percent. However, such a correction seems unreasonable because there is no evidence for a regional high temperature event in the midcontinent during the Pleistocene. Even if annealing occurred at ambient temperature, one would not expect the same degree of spontaneous track diameter reduction in ashes having such diverse ages. Furthermore, these ashes are distributed over a large geographic area and have various amounts of overburden, in all cases presently less than 200 feet. Therefore, it seems unlikely that the similar degree of reduction in track diameters is due to pressure.

The above arguments suggest the decrease in track diameter and track loss are not as simply interrelated as presented by Storzer and Wagner (1969 and 1971). Evidence for this is also apparent from their work. Storzer and Wagner (1969) found no reduction in the mean diameter of spontaneous fission tracks in a 0.73 m.y. old tektite. However, extrapolations of their laboratory annealing experiments indicate if this tektite was held at 0^{o} C since it formed, the density of spontaneous tracks should have been reduced 30 percent. This reduction in track density should be revealed as a 15 percent reduction in the mean diameter of the spontaneous tracks as compared to the induced tracks. Similarly, Storzer and Wagner (1971) show only a 5 percent reduction in the mean diameter of spontaneous tracks as compared to the

diameter of induced tracks in a 36.0 m.y. old tektite. According to their laboratory annealing experiments, even if the tektite had been held at 0^{o} C since it formed, the density of spontaneous fission tracks in this tektite should have been reduced 20 percent. This reduction in spontaneous track density would be revealed as a 15 percent reduction in the spontaneous track diameter as compared to the induced track diameter.

Hence, the usefulness of laboratory annealing data resulting from experiments made at elevated temperatures over short periods of time is doubtful when extrapolated to geologic time--especially data gathered from experiments made using only moderately elevated temperatures. A reduction in the mean diameter of spontaneous tracks as compared to induced tracks does not indicate an age correction should automatically be applied.

As shown in Figure 1-3, I hypothesize fission tracks may be partially annealed at ambient temperature resulting in a diminished mean diameter of the tracks without a reduction in their density. In order for annealing to progress further, considerable more energy is required than available at ambient temperatures. However, once this energy 'threshold' is passed, annealing will proceed resulting in a further decrease in track diameters and a reduction in the density of tracks.

The apparent partial invalidity of the annealing experiments and the general agreement of my dates with those of

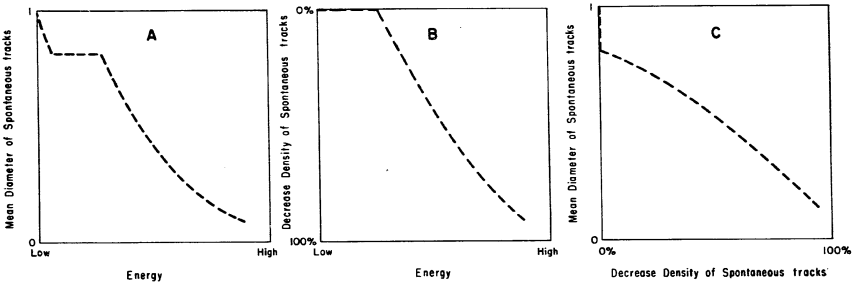

Figure 1-3. A Hypothetical Model for Fission Track Fading in Glass

The mean diameter of spontaneous fission tracks may be reduced to a limited degree at relatively low energy levels (A) without a decrease in the density of tracks (B). The degree to which this can occur is probably different for different materials. In order for the mean diameter of spontaneous tracks to be reduced further, somewhat higher energy levels are required. However, once this energy threshold is surpassed, further reductions in the mean diameter of the tracks (A) will be accompanied by a decrease in track density (B). Thus, as depicted in (C), a reduction in the mean diameter of spontaneous tracks would not be accompanied by a decrease in spontaneous tracks density until the energy threshold has been exceeded.

other workers leads me to believe an annealing correction is not needed for the ash ages presented in Table 1-1

I-2 Chemical Analyses of the Ashes

As pointed out earlier, Borchardt and others (1972) reported three ashes could be differentiated in the midcontinent on the basis of their manganese and samarium contents. They termed these the Green Mountain Reservoir ash, Pearlette-like ash, and the Bishop ash. Izett and others (1970) showed the Pearlette-like ash deposits could be further differentiated into a type-O ash and a type-S ash based on iron content and mineralogy. In light of their findings, I decided to analyze the ashes for iron, manganese, and samarium only.

Triplicate analyses of samarium were made by neutron activation analysis. A 10 cc sample of the finer-grained ash (149-62 micron) saved during the cleaning phase for fission track dating was further purified by: (i) heavy liquid separations using a bromoform-acetone mixture with a specific gravity of 2.34, (ii) leaching in concentrated hydrochloric acid, (iii) leaching in 30 percent hydrogen peroxide, (iv) magnetic separations, and (v) rinsing in 1:1 HCl, then distilled water, and finally acetone. Three subsamples were then split out of the dried material and placed into 1/2 dram polyethylene vials. Samples of solution standards and the U.S. Geological Survey standard rock G-2

were placed into separate vials.

All of the samples and standards were simultaneously irradiated for one hour in the graphite section of the Georgia Institute of Technology Research Reactor. A flux of about 5 X 10^{11} neutrons/cm^2/ second was used. Seven days later the activity of Sm^{153} in the samples and standards was measured with a 30-cc Ge(Li) detector connected to a 400-channel multichannel analyzer. Six determinations of Sm in Standard rock G-2 yielded a value of 8.6 ± 1.3 ppm as compared to a literature value of 8.3 ppm (Flanagan, 1969).

Duplicate iron and manganese analyses were made on separate splits from the remainder of the sample material cleaned for neutron activation analysis. Standard atomic absorption spectometry techniques and solution standards were used.

Results of these analyses are presented in Figure 1-4. These results are vey similar to those obtained by Borchardt and others (1972) and Izett and others (1970). The Pearlette ash (restricted), the Hartford ash, and the Borchers ash are chemically very similar even though these ashes have diverse fission tracks ages (ash terminology will be discusses later). Conversely, the Hartford ash and the Bishop ash have different compositions even though their ages are not significantly different. Thus, the age and chemical data presented in Table 1-1 and Figure 1-4 show there are five ashes having four significantly different ages.

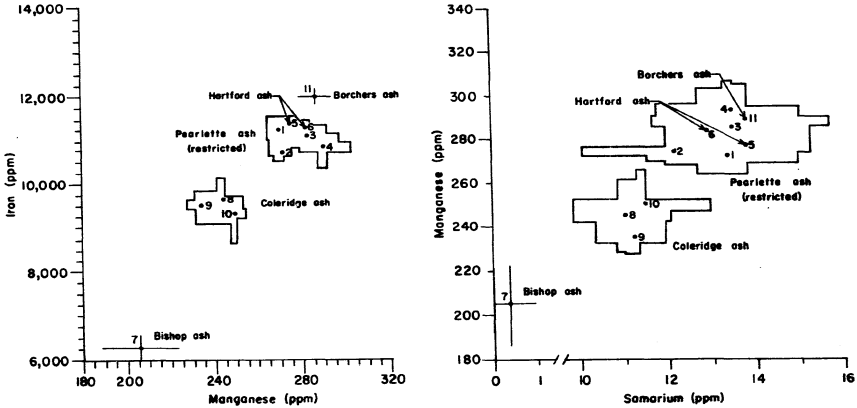

Figure 1-4. Relationships of the concentration of selected chemical elements in the ash shards. Numbers correspond to those in Figure 1-1 and Table 1-1. Dots are mean values with solid lines showing standard deviations.

I-3 Proposed Ash Nomenclature

The data presented in this paper indicate the informal terminology employed by Izett and others (1970) and Naeser and others (1971) should be discontinued. There are several factors, in part interrelated, which in my opinion will lead to undue confusion if their terminology is followed. First, the type-O ash and type-S ash designations are based on composition and hence are chemical types (with subsequent age connotations being inferred from K-Ar dates on hypothesized source rocks) whereas the type-B ash designation is based on a radiometric date rather than composition. Second, age and composition data (Table 1-1 and Fig. 1-4) indicate there are three ages of ash having the chemistry of Izett and others (1970) type-O ash. These three ages of ash are about 0.61 m.y., 0.74 m.y., and 1.97 m.y.

The fission-track ages presented in Table 1-1 indicate the type-O designation already has been applied to two different ages of ash. The ash at the Cudahy Ash Mine, Kansas; at Hartford, South Dakota; and at the County Line Section, Iowa, have all been assigned the type-O designation (Izett and others, 1971 and Naeser and others, 1971.

In order to avoid the confusion outlined above and to retain the firmly entrenched term "Pearlette ash", the following nomenclature for the ashes occurring in the midcontinent U.S.A. is proposed.

Ashes whose shards have a fission track age of about

0.6 m.y. and contain about 1.1 percent Fe, 280 ppm Mn, and 13 ppm Sm are herein designated Pearlette ash (restricted). The reference locality for Pearlette ash (restricted) is the Cudahy Ash Mine in the SW 1/4 sec. 2, T. 31 S., R. 28 W., Meade County, Kansas.

Ashes whose shards have a fission track age of about 0.7 m.y. and contain about 1.1 percent Fe, 280 ppm Mn and 13 ppm Sm are herein designated Hartford ash. The reference locality for the Hartford ash is in the SW 1/4 NE 1/4 sec. 11, T. 102 N., R 51 W., Minnehaha County, South Dakota.

The name Bishop ash, which Izett and others (1970) applied to the ash in Nuckolls County, Nebraska (Table 1-1, loc. no. 7) should be retained for thos ashes whose shards have a fission-track age of about 0.8 m.y. and contain about 0.6 percent Fe, 200 ppm Mn, and less than 5 ppm Sm.

Ashes whose shards have a fission track age of about 1.2 m.y. and contain about 1.0 percent Fe, 240 ppm Mn and 11 ppm Sm are herein designated Coleridge ash. The reference locality for the Coleridge ash is in the NE 1/4 NE 1/4, sec. 11, T. 29 N, R. 1 E., Cedar County, Nebraska.

Ashes whose shards have a fission track age of about 1.9 m.y. and contain about 1.2 percent Fe, 280 ppm Mn and 14 ppm Sm are herein designated Borchers ash. The reference locality for the Borchers ash is in the NW 1/4 NE 1/4, sec. 21, T. 33 W., R. 28 W., Meade County, Kansas.

Chemical analyses presented by Borchardt and others (1972) and Izett and others (1970) show that the Green Mountain

Reservoir ash is chemically distinct from the five ashes above. No occurrences of the Green Mountain Reservoir ash are known in the study area.

The proposed nomenclatural system requires knowledge of both the composition and fission track age of the ash shards. Chemical data presented in this report and those presented by other workers (Borchardt and others, 1972; Izett and others, 1970) were incorporated into the system. The nomenclatural system presented here is flexible because if new ash beds are discovered, they can be given names on the same basis as those above.

II. DIFFERENTIATION AND CORRELATION OF GLACIAL TILLS

Prior to the concept of a glacial origin of drift, it was believed that surficial deposits of boulder clay, sand, gravel and silt were formed by icebergs dropping foreign rocks on the surface during a period of submergence beneath the sea. The term drift was applied to these surficial deposits. The glacial origin of drift did not gain general acceptance in North America until about 1900 (Flint, 1949).

Before 1860 it was believed that only one episode of drift deposition had occurred in North America. During the 1860's several students of the "surficial deposits" presented evidence which indicated there were two episodes of drift deposition in the midcontinental U.S.A. (Worthen, 1868; White, 1870; Orton, 1871 and 1873; Winchell, 1872 and 1874; and McGee, 1878). Their evidence usually consisted of the presence of peat or "forest beds" occurring between layers of boulder clay or other drift deposits. Since this first departure from a simple concept of a single drift episode or glaciation, the problems of differentiation and correlation of glacial deposits have been compounded as the multiplicity of glaciation has come to be realized.

Evidence of multiple glaciation in the study area during the early Pleistocene was first presented by Reed and Dreeszen (1965) and Reed and others (1966). This evidence was derived in large part from subsurface data gathered in both the

glacial and the periglacial[1] regions of Nebraska. Their major tools for correlation and differentiation were fossil soils, widespread unconformities, and the "Pearlette" volcanic ash horizon.

Reed and Dreeszen's basic premise in making correlations between the glacial and periglacial regions was "---the advance and retreat of continental glaciation had a controlling effect on the deposition and erosional history of the periglacial region..." (Reed and Dreeszen, 1965, p. 4) and in both regions recognizable soils and widespread unconformities were developed during the interglacials. In addition, they believed lesser retreats and advances of the glaciers could be recognized by the development of interstadial soils and periods of minor erosion.

In evaluating the voluminous subsurface and surface data available Reed and Dreeszen (1965, p. 5) concluded "... it is believed to be possible to differentiate in the periglacial region two related depositional sequences in the Nebraskan; three in the Kansan, three in the Illinoian, and three in the Wisconsinan which can be related to and correlated with two tills of Nebraskan, two or more tills of Kansan, three tills of Illinoian, and three tills of Wisconsinan age in eastern Nebraska or elsewhere in the northern midcontinent region."

They recognized there were correlation problems, especially between the glaciated and nonglaciated regions. These

[1]The term periglacial as used by Reed and Dreeszen (1965) and Dreeszen (1970) referred to the area beyond the limits of continental glaciation.

problems were attributed to incomplete depositional sequences, lithologic similarity of deposits of like origin but of different ages, burial by younger deposits, difficulties in interpreting the significance of paleosols, and the possibility that there was more than one volcanic ash horizon. Because of these problems and the interpretive nature of the correlations, they considered parts of their classification to be tentative in nature (personal communication E. C. Reed and V. H. Dreeszen, 1971). The tentative nature of their classification led them to warn fellow workers; "It is not proposed that the names herewith suggested for use in Nebraska be utilized in neighboring states unless there is a need for a more detailed subdivision of units now recognized in those states" (Reed and Dreeszen, 1965, p. 3).

In a later paper, Dreeszen (1970, p. 11) again indicates the tentative nature of the 1965 classification by stating "A classification chart of the Pleistocene deposits in Nebraska was prepared...in an attempt to relate evidence obtained from extensive subsurface investigation to surface features, at the same time retaining the framework concept of four major continental glaciations and three interglacial periods. Rock-stratigraphic units were named to replace time-stratigraphic names, the complexity of the pre-Wisconsinan glaciations was suggested, loessic equivalents of fluviatile deposits were recognized, and the relation of these deposits to glacial deposits were inferred." In the same paper (p. 10) Dreeszen points out that "Although the deposits in the periglacial

region merge with those in the glaciated area, correlation problems between the two areas still exist." He suggests the deposition of thick alluvial sediments in the periglacial region was probably directly related to crustal adjustments and only indirectly related to glaciation.

Additional evidence of multiple glaciation during the early and middle Pleistocene in the midcontinent has been noted in northeastern Kansas (Dort; 1965, 1966a, 1966b, and Bayne, 1968) and in eastern Nebraska (Reed and others, 1966).

Dort (1965) reported the presence of two tills overlying a sand and silt sequence resting on striated bedrock and underlying what was thought to be Illinoian (Loveland) age loess. He noted the presence of two weathering horizons in the sub-till silt and sand. The striations on the bedrock were assumed to be due to the Nebraskan glaciation and both weathering horizons in the sand and silt sequence were assumed to have formed during the Aftonian. Based on these interpretations he concluded both tills were Kansan.

In later papers, Dort (1966a, 1966b) reported the presence of superimposed tills overlying silt and gravel on a striated bedrock surface and overlain by loess believed to be Wisconsinan in age. The tills are separated by paleosols or weathering horizons. Here too, two zones of soil formation are present in the underlying silt. Following the logic presented in his earlier report (Dort, 1965), the bedrock striations were assigned a Nebraskan age. The soil below the oldest till was assumed to be the Aftonian. All four

tills were assigned to four stadial advances of the Kansan glacier.

Dort (1970, p. 3) states that "It is now known that evidence does exist for stadial fluctuations of both of the glaciations [Nebraskan and Kansan], and there are indications in northeastern Kansas and eastern Nebraska of at least three major subdivisions of each." However, he fails to document the evidence for three stadial fluctuations in the Nebraskan and, to my knowledge, evidence for this has not been presented.

The present understanding of the complexity of the glacial history of North America has evolved largely from the continual development and application of criteria for differentiating and correlating glacial deposits. Criteria that have been used for differentiating and correlating glacial deposits are soil horizons, fossils, oxidized and leached horizons, geomorphologic features, mineralogic and lithologic characteristics, boulder pavements, radiometric dates, and interstratified "key beds" of nonglacial material such as volcanic ash.

In the following pages the search for and selection of parameters for correlating glacial tills in eastern Nebraska and adjacent areas are discussed. The parameters are then determined for tills from several localities (see Fig. 2-1). Correlations of tills are made using the selected parameters and possible ramifications of these correlations are discussed.

Interpretations of stratigraphic relationships at some

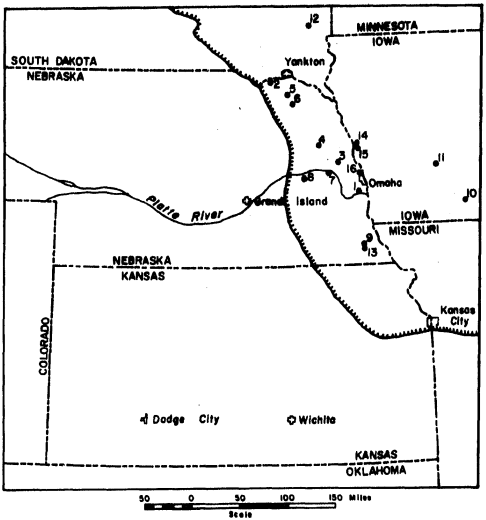

Figure 2-1. Location of sites where till samples were collected. For specific location see Figure 2-7. Hatchured line approximates maximum extent of continental glaciation in the study area (hatchures on glacier side).

of the localities studied have been important in the development of the classification of Pleistocene deposits in the Central Plains. For example, the stage names Nebraskan, Aftonian, and Kansan have their roots in interpretations of deposits near Afton, Iowa, and Florence, Nebraska, (Fig. 2-1, locs. 10 and 16, respectively).[2] Also, Illinoian till was interpreted to be present in northeastern Nebraska and southeastern South Dakota because of the occurrence of till above volcanic ash (believed to be the Pearlette Ash of late Kansan age) near Hartford, South Dakota, (Flint, 1955) and Coleridge, Nebraska, (Condra and Reed, 1950) [Fig. 2-1, locs. 12 and 6, respectively].

Historically, the development of concepts and techniques for differentiating and correlating glacial deposits have repeatedly altered previously accepted correlations. In view of this trend, it would be logical to assume future technological and conceptual developments will modify some of the conclusions presented in this report. The principal limiting factors to our understanding of the true complexity of the glacial history of the Pleistocene epoch may be the degree of refinement sought and the endurance and resourcefulness of the investigators.

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[2]Brief outlines of the development of the major divisions of the Pleistocene classification of North America and the development of the Pleistocene classification in Nebraska are presented in Appendices A and B respectively.

II-1. The Search for Till Correlation Parameters

The search for parameters useful for differentiating and correlating tills in the study area was facilitated by the presence of exposures of three superimposed tills at City Wide Rock Quarry near Omaha, Nebraska (Fig. 2-1, loc. 1 and Illustration 2-1). These tills are visually distinct and separated by weathering horizons indicative of a stable land surface being subjected to soil formation processes. Because of these factors, the City Wide Rock Quarry was chosen as the site for investigating the possibility of using internal characteristics of tills for correlation purposes. The methods used to study tills at this site and the results obtained will now be presented.

Grain size analyses

Channel samples of till were collected from two freshly scraped surfaces on the walls of the City Wide Rock Quarry (see Illustration 2-1). Grain-size distributions in these samples were analyzed using a slightly modified version of the method tentatively accepted by the American Society for Testing Materials (see Appendix H-1 for procedure). Particle size distribution curves were plotted, but they did not appear to be diagnostic. The relative percentages of sand (2.0 - .062 mm), silt (.062 - .004 mm), and clay (<.004 mm) in the samples are shown in Figure 2-2.

The data as depicted in these diagrams indicates the lower till is coarser grained than the other two and the

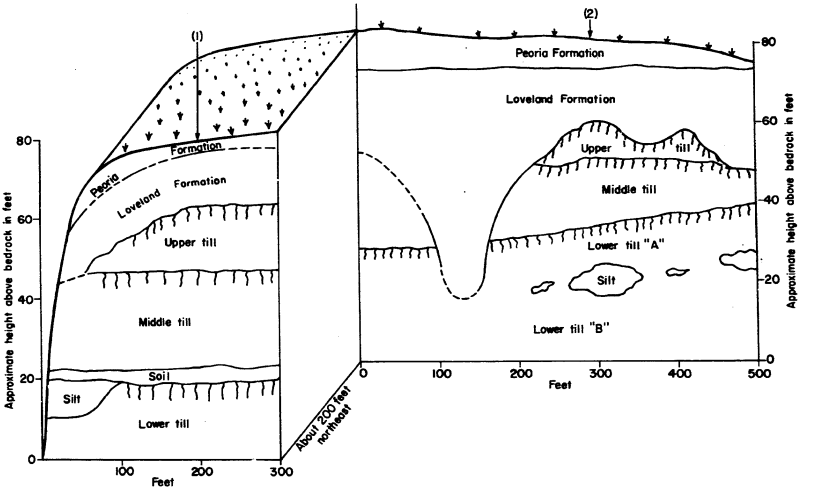

Illustration 2-1. Diagram of sediments exposed on a portion of the north wall of the City Wide Rock Quarry, Sarpy County, Nebraska. (1) Approximate location of measured Section 1. (2) Approximate location of measured Section 2.

grain-size distribution of lower till "A" above the silt-filled channels is very similar to that of the lower till "B". In general, the upper till is the finest grained and there is no overlap in the grain-size distribution of this till with the lower till. However, the grain-size distribution of the middle till shows considerable variation vertically and overlaps the distribution of both the upper and lower till--especially the upper till. As can be seen from the triangular plots in Figure 2-2, the variation in grain-size laterally between the two sections does not appear to be great.

As shown in Figure 2-2 the grain size of the three tills at the City Wide Rock Quarry fall predominantly into two groups. The group closest the clay portion of the diagram represents samples from the upper till and the upper part of the middle till; the other group represents nearly all the lower till samples and the lower samples from the middle till. Because of the overlapping grain-size of the tills at the City Wide Rock Quarry, the usefulness of grain-size analyses for differentiating and correlating tills in the study area appeared dubious.

Clay mineralogy

Clay mineralogy of the tills at the City Wide Rock Quarry - Section 1 was studied by applying standard X-ray techniques to the minus 2 micron-size clay saved during the grain-size study. Three samples from each the upper and middle tills and six samples of the lower till were analyzed. The

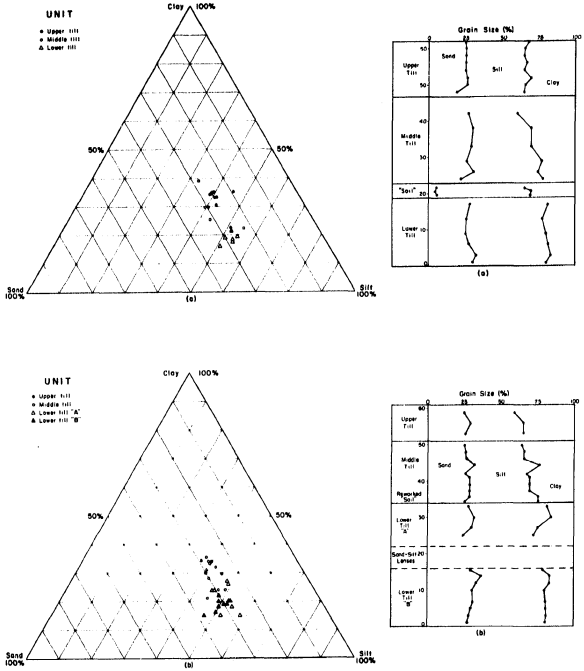

Figure 2-2. Grain-size distributions in tills at City Wide Rock Quarry. (a) Section 1, (b) Section 2 (see Illustration 2-1).

sample preparation procedure presented by Jackson (1956) was followed (see Appendix H-2).

Interpretations of the X-ray diffractograms are based on Jackson, 1956. The presence of a 7 Å peak (see Figure 2-3) in the air dried samples and in the glycolated samples along with the absence of a 7 Å peak in the heat treated sample is indicative of koalinite. The small peak, or shoulder, at about 10 Å in the air dried samples and a broad "hump" at about 10 Å in the glycolated samples probably indicates the presence of illite and/or micas. That part of the peak at about 14 Å in the air dried samples which expands to about 18 Å upon glycolation and collapses to about 10 Å upon heating to 500 °C is indicative of montmorillonite.[3] That part of the 14 Å peak in the air dried samples which remains at about 14 Å in the glycolated sample and is destroyed in the heat treated sample indicates the presence of vermiculite.

Although the clay mineralogy was examined only in a qualitative manner, the relative sizes of the diffraction peaks indicate that montmorillonite is the dominant clay mineral in the three tills. Vermiculite is probably the next most abundant followed by illite and kaolinite which are probably about equal in abundance.

Watts (1971) found that clays in a till[4] at various

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[3]Montmorillonite, as used here, refers to the magnesium saturated clay materials that expand to about 18 Å following glycerol treatment. In addition to montmorillonite, it may include mixed-layered and degraded clay minerals that are expandable.

[4]Presumably all of the till deposits studied were the Santee Till of Reed and Dreeszen (1965).

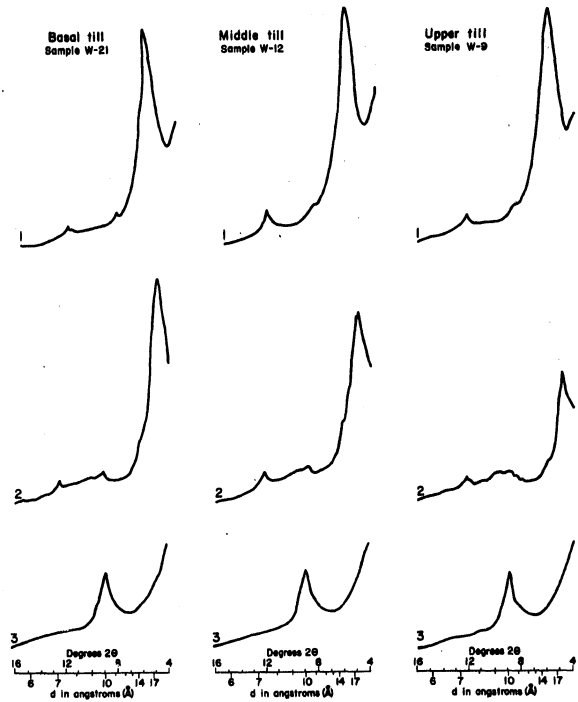

Figure 2-3. Smoothed tracings of typical x-ray diffraction patterns of magnesium saturated clay from three superimposed tills at City Wide Rock Quarry. 1. air dried; 2. glycolated; 3. air dried and heated to 500°C.

localities in northeast Nebraska consisted predominantly of smectite (80-95%)--most probably montmorillonite--with subordinate illite (1-15%) and kaolinite (less than 10%).

The mineralogy of the clays in the three tills at City Wide Rock Quarry and in the Santee Till in northeastern Nebraska appears to be nearly the same. Therefore, further studies of clay mineralogy as a parameter for distinguishing and correlating tills in the study area were abandoned.

Heavy minerals

Heavy minerals (sp. gr. >2.85) in the very fine sand fraction (.062 - .125 mm) of the till samples collected for textural analysis from City Wide Rock Quarry were separated using standard techniques (see Appendix H-3 for procedure). The heavy minerals were not digested in hydrochloric acid because a preliminary examination showed that soluble iron compounds (hematite and limonite) were usually present as discrete grains rather than as coatings on other minerals. Therefore, the grains of soluble iron compounds are probably a primary component of the till and not diagenetic.

A detailed study of the heavy mineral composition of three "grab" samples from each of the tills at the City Wide Rock Quarry was made. Three hundred grains from each sample were identified using a Leitz ortholux microscope and point count stage. Identifications were based largely on detrital mineral keys presented by Tickell (1947) with supplementary use of other standard mineralogical references.

Identification of heavy minerals was arduous because of

the large number of species present. The ice that deposited the tills travelled over sedimentary, metamorphic, and igneous terrains and incorporated deeply weathered to fresh material from each. Thus, ultrastable to unstable minerals from an indeterminate number of rock types occur together in the heavy mineral suite of the tills. Therefore, mineral associations and mineral stability were of little or no aid in identification.

As shown in Table 2-1 the results of the preliminary heavy mineral study indicated most of the mineral species were of little value in differentiating tills at City Wide Rock Quarry--especially in differentiating the upper till from the middle till. The most diagnostic minerals were hornblende, limonite, hematite, ilmenite, leucoxene, biotite, and garnet. The total percentage of opaque mineral species seems to be as useful as the percentage of individual opaque mineral species for differentiating the tills. Therefore, to facilitate further heavy mineral studies 300 grains per sample were counted and classified as hornblende, biotite, garnet, total opaque minerals, and "others."

As shown in Figure 2-4 the three tills at City Wide Quarry are quite distinct with respect to hornblende + biotite + garnet vs. total opaque minerals vs. "others." The middle till shows the greatest amount of variation as it did with respect to grain-size analysis. However, with respect to heavy minerals, there is no overlap between the middle and lower tills and only relatively minor overlap between the

Table 2-1. Results of Preliminary Heavy Mineral Study of Tills at City Wide Rock Quarry - Section 1[1]

	Sample Point[2]	Andalusite	Apatite	Basaltic Hornblende	Beryl	Biotite	Chloritoid	Epidote	Garnet	Hematite	Hornblende	Hypersthene	Ilmenite + Magnetite	Kyanite	Leucoxene	Limonite	Monazite	Muscovite	Pyrite	Rutile	Sphene	Spodumene	Staurolite	Topaz	Tourmaline	Zircon	Total Opaques
Upper Till	60	4.0	1.0	0.3	0.0	4.0	0.3	20.7	4.0	3.7	27.7	1.0	8.3	1.3	4.0	11.7	2.0	1.0	0.3	0.0	1.7	0.0	0.0	0.7	1.0	1.0	28.0
	55	4.0	0.3	0.0	0.3	7.0	0.0	16.0	9.0	2.7	29.3	0.0	7.9	3.0	4.0	3.0	6.3	1.3	0.3	0.3	3.3	0.7	0.0	0.0	0.0	1.3	18.0
	49	1.7	1.0	0.0	1.7	2.0	0.3	18.6	7.3	1.0	35.0	2.0	10.3	0.3	3.0	4.4	1.3	0.0	0.7	0.0	4.7	0.7	0.3	1.0	0.7	2.0	19.4
Middle Till	41	4.0	0.7	0.0	1.3	2.7	0.0	16.3	3.0	1.3	26.0	0.3	12.0	1.0	2.7	17.7	4.3	0.3	0.3	0.7	1.7	0.0	1.0	1.0	0.3	1.3	34.0
	32	6.3	0.7	2.0	0.3	5.0	1.7	11.7	5.3	4.0	19.3	0.0	12.0	0.7	4.7	12.3	6.0	1.3	1.0	0.0	3.0	0.0	0.0	1.7	0.0	1.0	34.0
	24	2.0	0.7	0.7	0.0	2.3	0.7	17.3	8.3	5.3	18.0	0.0	16.3	0.7	4.3	13.0	1.0	0.0	1.0	0.7	3.7	0.3	0.7	1.7	0.3	1.0	39.7
Lower Till	16	1.3	0.0	1.0	0.0	1.0	0.7	10.7	6.3	8.3	7.0	1.0	7.3	0.0	8.0	39.3	0.7	1.0	1.7	0.3	3.0	0.0	0.0	0.0	0.3	1.0	64.6
	8	1.7	0.0	1.0	1.0	3.0	0.7	10.0	3.3	6.3	9.7	0.3	11.6	0.7	12.0	28.7	0.3	1.0	1.3	0.0	4.3	0.0	0.0	0.7	0.7	1.7	59.9
	2	0.0	0.3	0.0	0.7	0.7	1.3	13.0	3.7	5.7	9.0	2.0	18.3	0.0	7.7	26.3	2.0	0.0	1.3	0.7	3.7	0.3	0.0	0.0	1.0	2.3	59.3

[1] All values are percent.
[2] Feet above bedrock.

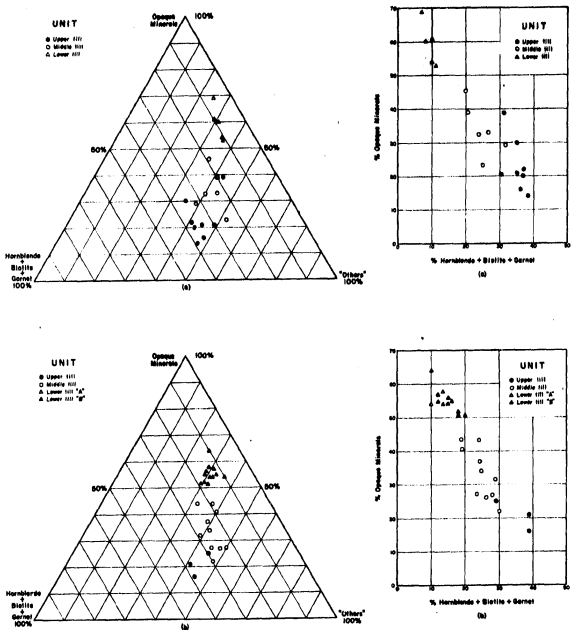

Figure 2-4. Relationships of selected heavy minerals from the 0.062-0.125 mm sand fraction of the tills at City Wide Rock Quarry. (a) Section 1 (b) Section 2 (see Illustration 2-1).

middle and upper tills. Note that hornblende + biotite + garnet content increases vertically up the section whereas the opaque minerals content decreases.

A comparison of the triangular plots in Figure 2-4 indicates there is little variation in the proportion of heavy mineral types between the two sections. Also, there does not appear to be a significant difference between lower till "A" and lower till "B" at section 2.

As shown in Table 2-2 the percent of heavy minerals in the very fine sand fraction is quite consistent--within a sample, within a till at a particular site, and within a till between sites. The samples from the lower till appear to be considerably poorer in heavy minerals than those from the middle and upper tills. The latter tills are nearly identical with respect to percent heavy minerals in the very fine sand fraction.

Light minerals

The percentage, by weight, of light minerals (sp. gr. <2.85) soluble in hydrochloric acid (HCl) was determined for the very fine sand fraction (0.062 - 0.125 mm) of the till samples collected for textural analysis from City Wide Rock Quarry - Section 2. The relative proportions of quartz, potash feldspar, and plagioclase feldspar in the residue were determined using standard staining and point count procedures. The staining procedure used is that presented by Reeder and McAllister (1956) and outlined in Appendix II-4.

As shown in Table 2-3 the relative proportions of potash

Table 2-2. Miscellaneous heavy mineral data from the tills at the City Wide Rock Quarry.

	City Wide Rock Quarry-Section 1			City Wide Rock Quarry-Section 2		
	Sample No.	Percent Heavy Minerals[a]	Percent Magnetic Heavies[b]	Sample No.	Percent Heavy Minerals[a] Trial 1	Trial 2
Upper Till	1	2.3	3.2	1	2.2	2.2
	2	2.3	3.2	2	2.6	2.6
	3	2.2	3.2	3	2.2	2.2
	4	2.2	2.7			
	5	2.4	3.6		2.3 ± .2	2.3 ± .2
	6	2.5	3.1			
	7	2.2	1.9			
	8	2.4	1.0			
		2.3 ± .1	2.7 ± .9			
Middle Till				4	3.1	2.8
				5	3.3	3.3
				6	3.0	3.5
				7	1.9	2.8
				8	2.8	2.6
	9	3.0	0.7	9	2.4	2.1
	10	2.4	1.7	10	2.5	2.4
	11	2.2	1.0	11	2.5	2.5
	12	2.0	2.9	12	---	3.1
	13	2.4	2.3	13	2.2	2.2
	14	2.0	---			
		2.3 ± .4	1.7 ± .9		2.6 ± .5	2.6 ± .5
Lower Till "A"				14	1.8	1.8
				15	2.0	2.0
				16	1.9	1.9
				17	1.7	1.4
	15	1.7	2.3			
	16	1.7	2.5		1.9 ± .1	1.8 ± .3
	17	1.4	1.6			
	18	1.9	2.4			
	19	1.7	2.5			
		1.7 ± .2	2.3 ± .4			
Lower Till "B"				18	1.6	1.7
				19	1.5	1.6
				20	1.5	1.5
				21	1.5	1.6
				22	1.7	1.7
				23	1.7	1.7
				24	1.7	1.9
				25	1.7	1.7
					1.6 ± .1	1.7 ± .1

a. As determined on the 0.062 - 0.125 mm sand fractions.
b. Those removeable with a hand magnet.

Table 2-3. Mineralogy of the "Light" Minerals from the City Wide Rock Quarry - Section 2.

	Sample No.	Weight Percent Acid Soluble[1]	Composition of Residue[2]		
			Potash Feldspar	Plagioclose Feldspar	Quartz
Upper till	1	2.9	0.0	1.0	99.0
	2	1.9	0.3	1.7	98.0
	3	3.1	0.0	0.7	99.3
		2.6 ± .6	0.1 ± .2	1.1 ± .5	98.8 ± .7
Middle till	4	8.8	0.7	0.7	98.4
	5	9.4	0.0	0.7	99.3
	6	8.8	0.0	0.0	100.0
	7	8.7	0.0	0.7	99.3
	8	7.0	0.7	1.0	98.3
	9	7.7	1.0	0.7	98.3
	10	7.3	1.0	1.0	98.0
	11	9.4	1.7	1.3	97.0
	12	28.6	1.7	0.7	97.6
	13	18.4	0.3	0.3	99.4
		11.4 ± 6.9	0.7 ± .7	0.7 ± .3	98.6 ±.9
Lower till "A"	14	12.4	0.0	0.3	99.7
	15	9.6	0.0	0.0	100.0
	16	5.3	0.0	0.3	99.7
	17	4.8	0.0	0.3	99.7
		8.0 ± 3.6	0.0 ± .0	0.3 ± .3	99.8 ±.2
Lower till "B"	18	6.1	0.0	0.3	99.7
	19	5.5	0.0	0.0	100.0
	20	4.6	0.0	0.7	99.3
	21	3.3	0.0	0.0	100.0
	22	3.6	0.3	0.7	99.0
	23	4.9	0.0	0.0	100.0
	24	5.7	0.0	0.0	100.0
	25	4.6	0.0	1.0	99.0
		4.8 ± 1.0	0.0 ± .1	0.3 ± .4	99.6 ±.5

[1]Determined from the .062-.125 mm sand fraction.
[2]Values are percent of residue after acid treatment.

feldspar, plagioclase feldspar, and quartz in the fine sand fraction of the tills are not diagnostic. The percentage of light minerals soluble in HCl is small in the upper till compared to the lower tills. This is probably due to the matrix of the upper till being leached at Section 2. The high percentage of acid soluble light minerals at the base of the middle till is probably due to the incorporation of local bedrock (as indicated by blocks of local limestone) and/or incorporation of secondary lime grains from the lime accumulation zone in the underlying till. The higher values in the upper part of the lower till "A" are probably also due to the presence of grains of secondary lime.

Pebble counts

Pebble samples were collected on freshly scraped surfaces from both sections (see Illustration 2-1) at the City Wide Rock Quarry (see Appendix G for sample interval). The freshly exposed till was manually broken apart in the field and grains larger than very coarse sand were collected. If a large boulder was encountered, only a chip was taken.

The pebbles were air dried, soaked in a .01 N sodium oxalate solution to disperse adhering clay and silt, then wet sieved over the #5 sieve (4 mm). Care was taken at this stage to remove the >4 mm pebbles, such as shale or deeply weathered "granitic" rocks which were fragile. The >4 mm pebbles were then dried and identified with the aid of a binocular microscope. Limestone and dolomite were differentiated by acid reaction and other pebbles were broken to examine fresh

surfaces.

The pebbles were placed into classes shown in Appendix G. In part, these classes are arbitrary. For example, pebbles consisting only of quartz were classified as sedimentary pebbles; pebbles consisting predominantly of quartz and containing a trace or more of mafic minerals were classified as "metamorphic other"; and pebbles consisting predominantly of quartz and containing minor amounts of feldspar were classified as "plutonic." Also, many of the pebbles classified as "granite" are probably of metamorphic origin.

Although the classification scheme may be somewhat arbitrary, it is of little consequence for the purpose of differentiating the tills. The main requirement of the classification is that pebbles be identified in a consistent manner from sample to sample. To check the consistency of identifications, most of the pebble samples were recounted by Mr. Howard McNiff, a geologist employed by the Nebraska Geological Survey. In nearly all cases, our results agreed within a few percent--especially with respect to the major categories; sedimentary, metamorphic, and plutonic.

Numerous graphs showing the relationships between individual pebble classes and combinations of classes were made. As shown in Figure 2-5 this trial and error method of analysis indicates relationships of sedimentary, metamorphic, and plutonic classes are useful for differentiating tills at City Wide Rock Quarry. The proportion of pebble types in basal samples, collected from within a few feet of the base of a

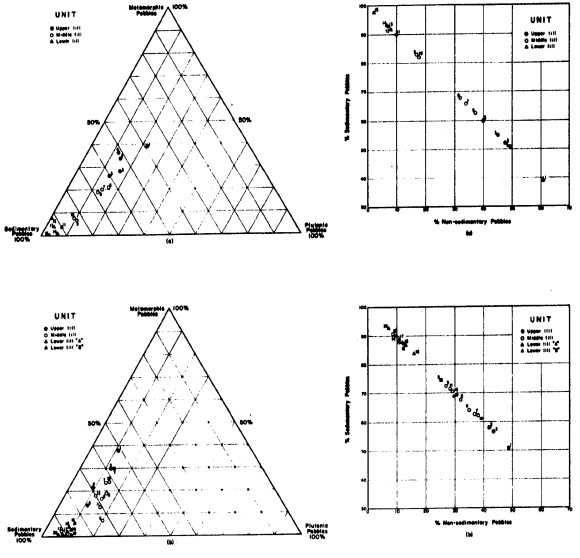

Figure 2-5. Relationships of sedimentary, metamorphic, and plutonic pebbles from the tills at City Wide Rock Quarry. (a) Section 1, (b) Section 2 (see Illustration 2-1). The samples are numbered consecutively from top to bottom of the section.

till, is similar to the pebble composition of the underlying till [see Figure 2-5 (a), points 9 and 10 and Figure 2-5 (b), points 4, 5, and 13]. Figure 2-5 also shows that the porportion of pebble types within each till is similar at sections 1 and 2--especially if the basal samples are disregarded. In addition, the proportion of pebble types in lower till "A" and lower till "B" at section 2 seems to be about the same. Thus, pebble composition serves to differentiate tills at the City Wide Rocky Quarry, especially if the basal samples are omitted. Except for these latter samples, there is little overlap in the pebble composition of the tills.

Figure 2-5 shows the tills become progressively poorer in sedimentary pebbles and richer in metamorphic pebbles going upsection. The content of plutonic pebbles also increases upsection; however, this trend is not as dramatic.

II-2 Selection and Application of Correlation Parameters

Analyses of tills at the City Wide Rock Quarry demonstrates that heavy minerals from the very fine sand fraction (0.062 - 0.125 mm) and pebble types from the >4 mm fraction would serve to differentiate these tills. Grain size, clay minerals and "light" minerals were not diagnostic. Consequently, only the types of pebbles and heavy minerals in till samples collected from various localities in Iowa, Nebraska, and South Dakota (see Fig. 2-1) were examined.

Samples were collected from freshly scraped surface exposures, rotary drill cuttings, and auger drill cuttings. Samples from drill holes were normally taken every five feet.

In rotary drilling, all cuttings were circulated from the hole after drilling each five-foot interval. With auger drilling, samples were collected by ramming the auger five or ten feet into the till, then pulling the auger. Cuttings from the auger were grouped into five-foot intervals. Both auger and rotary-drill samples were broken apart and grains larger than very coarse sand were collected for pebble counts. Samples of the till were also bagged for heavy mineral analyses.

Three or more samples were usually collected from each till, but in some cases only one or two samples could be obtained because the till was thin or only partially exposed. Also, the entire thickness of some of the tills is not represented by samples because of incomplete exposure or burial beneath thick overburden. The auger drill was equipped with only 100 feet of auger.

In the laboratory, about 50 grams of each the air dried till samples were dispersed in a 0.01 N sodium oxalate solution and wet sieved over the #230 sieve. The residue was oven dried and the 0.062 - 0.125 mm sand fraction removed by sieving. Heavy minerals were separated from this fraction using Bromoform (see procedure outlined in Appendix H-3). The heavy minerals were mounted in Canada Balsam and 300 grains were classified as hornblende, biotite, garnet, total opaque minerals, and "others". The pebble samples were treated as outlined earlier.

The basic heavy mineral and pebble count data for the

samples from the till localities studied are presented in Appendix G.

Data Manipulation

Numerous problems arose during the analysis of the heavy mineral and pebble count data. These problems proved to be a result of several factors. These factors are: the presence of vertical compositional gradients acting in opposing direction from one till to another, severe weathering and leaching of some tills, local incorporation of an older till into the basal part of a younger till, incomplete sampling of some till bodies because of incomplete exposure or drill penetration, and the failure to collect paired samples for heavy mineral analyses and pebble counts. These factors ultimately limited the analysis of the pebble count and heavy mineral data to comparisons of mean values for each heavy mineral and pebble class for each till at each locality.

As shown earlier, either heavy mineral analyses or pebble counts alone were sufficient to differentiate the tills at City Wide Rocky Quarry. However, subsequent analysis of data from other tills indicated both criteria were needed to differentiate the various tills.

Because both pebble count and heavy mineral data were found to be necessary to distinguish tills throughout the study area, these types of information had to be combined. The simples method for combining this information would be to collect paired samples at all localities. Because the

need for this was not realized until after the sampling was completed, the same number of samples for pebble count and heavy mineral analyses were not always collected. Also, samples for these analyses were not always taken at the same position in the section. To circumvent this lack of paired samples, the samples from each till body were classified into groups of upper, middle, and lower portions of the till body or exposure. An average value for each heavy mineral and pebble class was calculated for the upper, middle, and lower part of each till.[5] These averages for pebble counts and heavy minerals effectively formed paired samples for the upper, middle, and lower parts of each till sampled.

Some samples were omitted when computing the means because there were strong indications that carbonate pebbles had been removed by leaching. Samples omitted because of leaching were the uppermost sample at the David City Ash Locality, the type locality of the Clarkson Till, the City Wide Rock Quarry - Section 1 and the two uppermost samples of the lower till at Afton, Iowa.

Pebble counts from a till directly overlying another till indicated a significant amount of the underlying till may be incorporated into the basal few feet of the overlying till. Consequently, several basal till samples that bore the compositional imprint of the underlying till were excluded in computing the averages for the upper, middle, and lower portions

[5]This data grouping is indicated by the dashed lines in the "Sample position" column in Appendix G.

of each till. Basal samples excluded from the averaging were the two lowermost samples of the upper till and the lowermost sample of the middle till at City Wide Rock Quarry - Section 2, and the two lowermost samples from the middle till at section 1 of the same site.

This secondary data consisting of paired heavy mineral and pebble count information for the upper, middle and lower parts of the tills is presented in Appendix 1. Graphs showing relationships of selected variables from these data were largely unsatisfactory because the values within a specific till had a considerable vertical range causing overlap in compositional values between tills. In addition to random variation, the range in values within a till appears to be due to vertical composition gradients--especially with respect to sedimentary pebble content. In addition to the above sources of variation, the overlap in values between tills is probably largely due to compositional gradients acting in opposing directions from one till to another. For example, the sedimentary pebble content of the tills at the City Wide Rock Quarry increases down section whereas it increases upsection at the type localities of the Santee, Clarkson, and Hartington Tills (see Figure 2-6 for terminology). Also, because of these gradients, the overlap between tills was probably affected by the fact that at some localities only the upper part of the till could be sampled.

Because of the problems outlined above, further analyses of the heavy mineral and pebble count data were restricted to comparisons of mean values for each heavy mineral and pebble

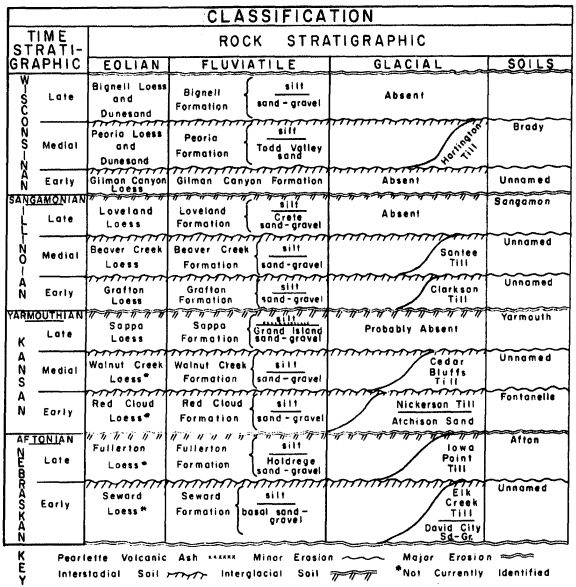

Figure 2-6. Classification of Pleistocene deposits of Nebraska (from Reed and Dreeszen, 1965).

class for each till at each locality (see Appendix 1). These values will be referred to as the mean compositional data in the following discussion.

Correlation coefficients (see Table 2-4) were calculated for selected relationships of the mean compositional data. The percentages of hornblende, biotite and garnet were added together in computing some of the correlation coefficients because of the likelihood these minerals represent a common assemblage in crystalline rocks.

Some inferences can be made about sources of the various heavy minerals from the correlation coefficients shown in Table 2-4. The highly significant positive correlation between hornblende and nonsedimentary pebbles and between hornblende + biotite + garnet and nonsedimentary pebbles indicates, as would be expected, these minerals were largely derived from crystalline rocks. Furthermore, comparison of the correlation of hornblende + biotite + garnet with the two nonsedimentary rock groups indicates the principal source of these minerals is rock types classed metamorphic (see Appendix G).

The highly significant positive correlation between opaque minerals and sedimentary pebbles along with the negative correlation of opaque minerals with metamorphic and plutonic pebble classes indicates opaque minerals were derived principally from the sedimentary terrain traversed by the glaciers.

The nonsignificant correlation of heavy minerals classed as "other" with the three pebble groups suggests these minerals

Table 2-4. Correlation Coefficients of selected Heavy Mineral and Pebble Data from Tills in Iowa, Nebraska, and South Dakota.

Relationship	Correlation Coefficient[1]
Hornblende vs. sedimentary pebbles	-0.72**
" vs. metamorphic pebbles	+0.77**
" vs. plutonic pebbles	+0.41*
(H+B+G)[2] vs. sedimentary pebbles	-0.75**
" vs. metamorphic pebbles	+0.76**
" vs. plutonic pebbles	+0.40*
Opaque minerals vs. sedimentary pebbles	+0.54**
" " vs. metamorphic pebbles	-0.57**
" " vs. plutonic pebbles	-0.32^{ns}
"Other" heavy minerals vs. sedimentary pebbles	-0.01^{ns}
" " " vs. metamorphic pebbles	-0.12^{ns}
" " " vs. plutonic pebbles	-0.14^{ns}

1 For n=28 and a significance level of 0.05, the correlation coefficient (r) must have an absolute value greater than 0.361 for the correlation to be significant (*). At a significance level of 0.01, r must have an absolute value greater than 0.463 for the correlation to be highly significant (**). Significance was determined from "Critical Values for Correlation Coefficients" (Rohlf and Sokal, 1969).

2 Hornblende+Biotite+Garnet

were derived in nearly equal proportions from all three terrains--sedimentary, metamorphic, and plutonic.

Using correlation coefficients as a guide, graphs were constructed showing relationships between selected mean composition data from the till deposits (see Figure 2-7).

The mean compositional data was also subjected to Q-mode factor analyses in an attempt to use all of the contained information.[6] Q-mode factor analysis is a statistical classification scheme which is capable of grouping samples by means of simultaneously evaluating all the variables. Factor analyses were performed using a library program[7] and an IBM 360-65 Computer at the University of Nebraska Computing Center. Results of the analyses are presented graphically in Figure 2-8. An example of the factor analysis output from the computer is presented in Appendix J.

The close correspondence between the graphs showing the relationship of selected variables (Figure 2-7) and the graphs based on factor analysis (Figure 2-8) indicates that factors 1 and 2 largely reflect hornblende plus nonsedimentary pebbles and opaque minerals plus sedimentary pebbles respectively. Furthermore, the results of the factor analysis indicate

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[6]In addition to the basic pebble and mineral classes, groups of variables found useful for differentiating the tills by graphical means were included in some of the factor analyses. This is permissible provided that such a priori knowledge of the underlying structure of the data is available (Imbrie and Van Andel, 1964). The percent calcareous sandstone, being small, was added to the "other" sedimentary pebble class.

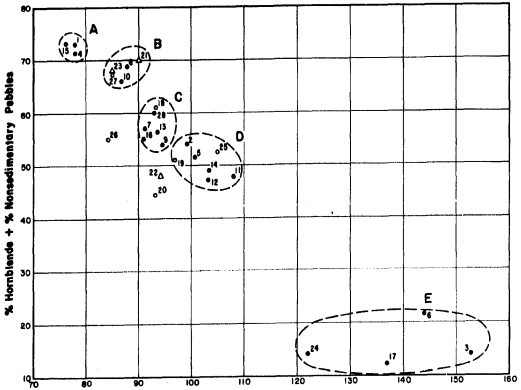
[7]The program was written by Paul Sampson and Robert I. Jennich, members of the staff of Health Sciences Computing Facility, UCLA.

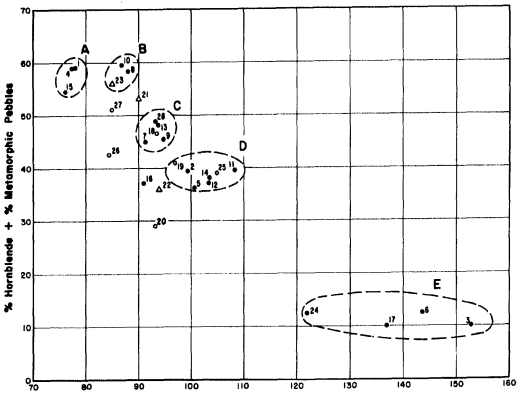
Point		Location	Unit
1	1*	City Wide Rock Quarry; NE 1/4 NW 1/4 sec. 29, T. 13 N, R. 13 E, Sarpy County, Nebraska - Section 1	Upper till**
2		" " " " " " "	Middle till**
3		" " " " " " "	Lower till**
4		City Wide Rock Quarry; NE 1/4 NW 1/4 sec. 29, T. 13 N, R. 13 E, Sarpy County, Nebraska - Section 2	Upper till**
5		" " " " " " "	Middle till**
6		" " " " " " "	Lower till**
7	2	Type locality Santee Till; SE 1/4 SE 1/4 NW 1/4 sec. 29, T. 33 N, R. 4 W, Knox County, Nebraska	Santee Till**
8	3	Type locality Nickerson Till; SE 1/4 SW 1/4 sec. 8, T. 18 N, R. 9 E, Washington County, Nebraska	Upper till**
9		" " " " " " "	Nickerson Till
10	4	Type locality Clarkson Till; SW corner SE 1/4 sec. 25, T. 22 N, R. 2 E, Stanton County, Nebraska	Clarkson Till
11	5	Type locality Hartington Till, SW 1/4 SW 1/4 sec. 13, T. 31 N, R. 1 E, Cedar County, Nebraska	Hartington Till
12	6	Coleridge Ash Site; NW 1/4 NE 1/4 NE 1/4 sec. 11, T. 29 N, R. 1 E, Cedar County, Nebraska	Till (above ash)**
13	7	Type locality Cedar Bluffs Till; SW 1/4 NE 1/4 NW 1/4 sec. 24, T. 17 N, R. 7 E, Saunders County, Nebraska	Cedar Bluffs Till**
14		" " " " " " "	Lower till
15	8	David City Ash Locality; SE corner sec. 32, T. 15 N, R. 3 E, Butler County, Nebraska	Upper till**
16		" " " " " " "	Lower till (above ash)**
17	9	Elk Creek Ash Site; SW 1/4 SE 1/4 sec. 26, T. 4 N, R. 11 E, Johnson County, Nebraska	Till below ash**
18	10	Type area of the Kansan and Pre-Kansan Tills of H. F. Bain (1896); NW 1/4 sec. 28, T. 72 N, R. 29 W, Union County, Iowa	Upper till (Kansan)**
19		" " " " " " "	Lower till (Pre-Kansan)
20	11	Guthrie Ash Site; SE 1/4 sec. 8, T. 78 N, R. 33 W, Guthrie County, Iowa	Till below ash
21	12	Hartford Ash Site; SW 1/4 NE 1/4 sec. 11, T. 102 N, R. 51 W, Minnehaha County, South Dakota	Upper till (above ash)**
22		" " " " " " "	Middle till (below ash)**
23		" " " " " " "	Lower till**
24	13	Type locality Elk Creek Till; NW 1/4 SW 1/4 sec. 1, T. 3 N, R. 11 E, Pawnee County, Nebraska	Elk Creek Till**
25	14	County Line Section, Iowa; NW 1/4 NE 1/4 sec. 5, T. 81 N, R. 44 W, Harrison County, Iowa	Till (below ash)
26	15	NE 1/4 NE 1/4 sec. 30, T. 81 N, R. 44 W, Harrison County, Iowa	Upper till**
27		" " " " " " "	Lower till
28	16	Type area of the Nebraskan till (Shimek, 1909); East line NE 1/4 SW 1/4 sec. 16, T. 16 N, R. 13 E, Douglas County, Nebraska	Nebraskan Till

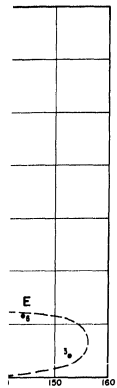
*Location numbers correspond to those on the Generalized Location Map (see Figure).

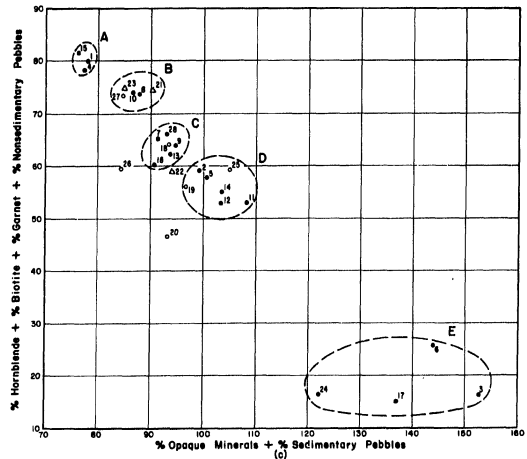
**Upper and lower till boundary determined and the till sampled at selected intervals throughout.

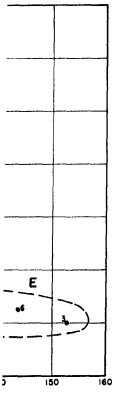
Figure 2-7. Relationships of Selected Heavy Mineral and Pebble Count Data from tills in Iowa, Nebraska, and South Dakota. Block letters refer to clusters of points bounded by dashed lines. (•) denotes those samples from Nebraska, (◦) those from Iowa, and (▲) those from South Dakota.

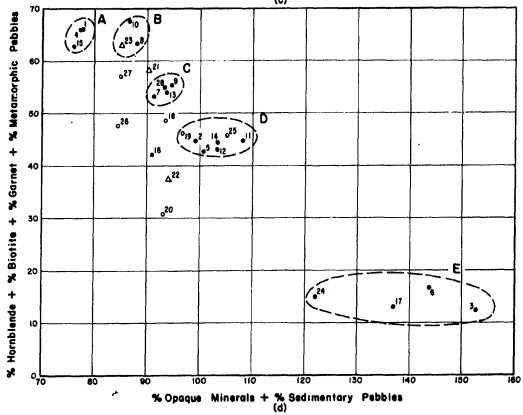












Point		Location	Unit
1	1*	City Wide Rock Quarry; NE 1/4 NW 1/4 sec. 29, T. 13 N, R. 13 E, Sarpy County, Nebraska - Section 1	Upper till**
2		" " " " " " "	Middle till**
3		" " " " " " "	Lower till**
4		City Wide Rock Quarry; NE 1/4 NW 1/4 sec. 29, T. 13 N, R. 13 E, Sarpy County, Nebraska - Section 2	Upper till**
5		" " " " " " "	Middle till**
6		" " " " " " "	Lower till**
7	2	Type locality Santee Till; SE 1/4 SE 1/4 NW 1/4 sec. 29, T. 33 N, R. 4 W, Knox County, Nebraska	Santee Till**
8	3	Type locality Nickerson Till; SE 1/4 SW 1/4 sec. 8, T. 18 N, R. 9 E, Washington County, Nebraska	Upper till**
9		" " " " " " "	Nickerson Till
10	4	Type locality Clarkson Till; SW corner SE 1/4 sec. 25, T. 22 N, R. 2 E, Stanton County, Nebraska	Clarkson Till
11	5	Type locality Hartington Till, SW 1/4 SW 1/4 sec. 13, T. 31 N, R. 1 E, Cedar County, Nebraska	Hartington Till
12	6	Coleridge Ash Site; NW 1/4 NE 1/4 NE 1/4 sec. 11, T. 29 N, R. 1 E, Cedar County, Nebraska	Till (above ash)**
13	7	Type locality Cedar Bluffs Till; SW 1/4 NE 1/4 NW 1/4 sec. 24, T. 17 N, R. 7 E, Saunders County, Nebraska	Cedar Bluffs Till**
14		" " " " " " "	Lower till
15	8	David City Ash Locality; SE corner sec. 32, T. 15 N, R. 3 E, Butler County, Nebraska	Upper till**
16		" " " " " " "	Lower till (above ash)**
17	9	Elk Creek Ash Site; SW 1/4 SE 1/4 sec. 26, T. 4 N, R. 11 E, Johnson County, Nebraska	Till below ash**
18	10	Type area of the Kansan and Pre-Kansan Tills of H. F. Bain (1896); NW 1/4 sec. 28, T. 72 N, R. 29 W, Union County, Iowa	Upper till (Kansan)**
19		" " " " " " "	Lower till (Pre-Kansan)
20	11	Guthrie Ash Site; SE 1/4 sec. 8, T. 78 N, R. 33 W, Guthrie County, Iowa	Till below ash
21	12	Hartford Ash Site; SW 1/4 NE 1/4 sec. 11, T. 102 N, R. 51 W, Minnehaha County, South Dakota	Upper till (above ash)**
22		" " " " " " "	Middle till (below ash)**
23		" " " " " " "	Lower till**
24	13	Type locality Elk Creek Till; NW 1/4 SW 1/4 sec. 1, T. 3 N, R. 11 E, Pawnee County, Nebraska	Elk Creek Till**
25	14	County Line Section, Iowa; NW 1/4 NE 1/4 sec. 5, T. 81 N, R. 44 W, Harrison County, Iowa	Till (below ash)
26	15	NE 1/4 NE 1/4 sec. 30, T. 81 N, R. 44 W, Harrison County, Iowa	Upper till**
27		" " " " " " "	Lower till
28	16	Type area of the Nebraskan till (Shimek, 1909); East line NE 1/4 SW 1/4 sec. 16, T. 16 N, R. 13 E, Douglas County, Nebraska	Nebraskan Till

*Location numbers correspond to those on the Generalized Location Map (see Figure).

**Upper and lower till boundary determined and the till sampled at selected intervals throughout.

Figure 2-8. Results of Factor Analysis of Heavy Mineral and Pebble Count Data from Tills in Iowa, Nebraska, and South Dakota.

(a) Factor analysis using no linear combinations other than % sedimentary, % metamorphic, and % plutonic pebbles. (b) As above but with linear combinations hornblende + biotite + garnet + nonsedimentary pebbles and opaque minerals + sedimentary pebbles included in the data. (c) As with (b) but including hornblende + biotite + garnet in the data. (•) denotes those samples from Nebraska, (◦) those from Iowa, and (△) those from South Dakota.

that factors 1 and 2 account for about 97 percent of the total variation between the samples (see Appendix J). Thus, opaque minerals, hornblende, sedimentary pebbles, and non-sedimentary pebbles furnish nearly all the information needed to differentiate the tills. These data constitute about 75% of the total compositional data collected.

Interpretations and Discussion

Interpretations of the graphical and statistical analyses of the mean composition data is fairly easy when only those samples from Nebraska are considered. As can be seen in Figures 2-7 and 2-8 the composition of these samples generally falls into five well-defined clusters (labeled A thru E). As shown in Figure 2-9, tills having a composition represented by Cluster A are not associated with tills having a composition represented by Cluster B at any of the sections studied in Nebraska. Therefore, the sequence of tills in Nebraska, from younger to older, may be either ABCDE or BACDE. At multiple till sections studied in Nebraska, successively younger tills contain a smaller percentage of opaque minerals and sedimentary pebbles (see Figs. 2-7, and 2-9). Because Cluster B is richer with respect to these elements than Cluster A (see Figure 2-7); sequence ABCDE is favored.

Results of graphical and statistical analyses are not as easily interpreted for samples from outside Nebraska. This is especially true for the samples from Hartford, South Dakota; Harrison County, Iowa; and Guthrie County, Iowa. Figures 2-7 and 2-8 and Table 2-5 show the points representing

Figure 2-9. Correlation of till units based on Superposition and Interpretations of Heavy Mineral and Pebble Compositions. Block letters refer to till compositions as shown in Figures 2-7 and 2-8. Numbers in parentheses refer to location numbers on Figure 2-1 and 2-7.

Table 2-5. Summary of the Clustering of the Mean Till Compositions Based on Graphical and Statistical Interpretations

Point No.*	Graphical Interpretations (See Figures 2 - 7)				Statistical Interpretations (See Figures 2 - 8)		
1	A	A	A	A	A	A	A
2	D	D	D	D	D	D	D
3	E	E	E	E	E	E	E
4	A	A	A	A	A	A	A
5	D	D	D	D	D	D	D
6	E	E	E	E	E	E	E
7	C	C	C	C	C	C	C
8	B	B	B	B	B	B	B
9	C	C	C	C	C-D	C	C
10	B	B	B	B	B	B	B
11	D	D	D	D	D	D	D
12	D	D	D	D	D	D	D
13	C	C	C	C	C	C	C
14	D	D	D	D	D	D	D
15	A	A	A	A	A	A	A
16	C	D?	C	D?	C	C	C
17	E	E	E	E	E	E	E
18	C	C	C	D?	C	C	C
19	D	D	D	D	C	D?	D
20	D?	D?	D?	D?	C?	D	D
21	B	C-B	B	C-B	B	B	B
22	D?	D?	C-D	D?	C-D	D?	C-D
23	B	B	B	B	A	A-B	A-B
24	E	E	E	E	E	E	E
25	D	D	D	D	D	D	D
26	C?	C?	C?	C?	C	C	C
27	B	C-B	B	C-B	B	B	B
28	C	C	C	C	C	C	C

* These numbers correspond to those on Figure 2—7 and 2—8.

samples from these sites (Hartford, South Dakota, points 21, 22, and 23; Harrison County, Iowa, points 26 and 27; Guthrie County, Iowa, point 16) often do not fit into the five clusters. As can be seen in the figures and table the upper and lower tills at Hartford are similar in composition and are similar to the lower till at the Harrison County section. The middle till at Hartford has a composition similar to the till at the Guthrie County section.

How do the tills at the Hartford, South Dakota; Harrison County, Iowa; and Guthrie County, Iowa, sites correlate with the tills in Nebraska? Several alternative correlations are schematically shown in Figure 2-9. The correlations of alternative (c) yield the fewest number of tills, six, but are more interpretive than correlations using the other alternatives.

Are the intermediate compositions of the tills at the Hartford, South Dakota; Harrison County, Iowa, and Guthrie County, Iowa, sites a result of facies change or the presence of distinct till units? Although a definitive answer must await further work, the fact that the only known occurrences of the Hartford ash (see Table 1-1) are at the Hartford, South Dakota and Harrison County, Iowa, sites suggests the intermediate compositions of tills at these sites may be due to the presence of till units not preserved or deposited at the other localities studied.

The clusters shown in Figures 2-7 and 2-8 represent the compositions of till units from two or more localities. Each cluster may contain unnamed till units and/or till units with

formal stratigraphic names.

Cluster A is unique in that it contains no points representing type sections of formally designated till units. The till represented by points 1 and 4 was formerly correlated as Nickerson (Reed and others, 1966 - see Table 2-6) and that represented by point 15, was correlated as Cedar Bluffs (Dreeszen, 1970).

Cluster B contains only one point representing a type section of a formally designated till unit--the Clarkson Till of Reed and Dreeszen, 1965. However, superposition of tills at Hartford, South Dakota, (see Fig. 2-9) indicate two ages of till have the composition represented by this cluster.

Cluster C contains points representing type sections of five formally designated till units--the Santee, Nickerson, and Cedar Bluffs Tills of Reed and Dreeszen, 1965; the Nebraskan Till of Shimek, 1909; and the Kansan Till of Bain, 1896 and Chamberlin, 1896. Superposition and tentative correlations of tills at the Nickerson type locality and the Harrison County section (see Fig. 2-9, locs. 3 and 15) indicate two ages of till probably have the composition represented by this cluster.

Cluster D contains points representing type sections of two formally designated till units--the Hartington Till (Reed and Dreeszen, 1965) and the Pre-Kansan Till (Bain 1896, and Chamberlin 1896). This cluster also contains tills previously correlated as Santee (point 12, Reed and Dreeszen, 1965) and Nickerson (points 2 and 5; Reed and others, 1966 and point 14, Reed and Dreeszen, 1965).

Cluster E contains only one point representing the type section of a formally designated till unit--the Elk Creek Till (Reed and Dreeszen, 1965). Till deposits represented by points 3, 6, 17 and 24 were previously correlated as Elk Creek Till (Reed and others, 1966 and Reed and Dreeszen, 1965).

As is evident from the discussion above, correlations based on till composition and superposition of till units indicate serious problems may exist in the present terminology of Pleistocene deposits in the Central Plains. The correlations presented in Figure 2-9 indicate: (1) Shimek's (1909) Nebraskan Till (loc. 16) correlates with the upper till (Kansan Till of Bain, 1896 and Chamberlin, 1896) near Afton, Iowa (loc. 10) rather than the lower till (pre-Kansan); (2) the Elk Creek Till (locs. 1, 9, and 13) of Reed and Dreeszen, 1965 is older than both the classic pre-Kansan Till near Afton, Iowa and the Nebraskan Till of Shimek (1909) above Florence, Nebraska; (3) the type sections or areas of the Santee, Nickerson and Cedar Bluffs tills (locs. 2, 3, and 7) of Reed and Dreeszen (1965), the Kansan Till of Bain and Chamberlin (1896), and the Nebraskan Till of Shimek (1909) are part of the same till sheet; and (4) the Hartington Till of Reed and Dreeszen (1965) at its type locality (loc. 5) correlates with the pre-Kansan Till of Bain and Chamberlin (1896) near Afton, Iowa.

These correlations suggest the terms Elk Creek Till and Clarkson Till may be the only valid rock stratigraphic names presently applied to tills in the study area. The Elk

Creek Till is readily recognizable in the field because of its very high percentage of sedimentary pebbles (generally >90%). Other tills having a similar composition are not known in the study area.

The correlations shown in Figure 2-9 also indicate the usefulness of the terms Nebraskan, pre-Kansan, Kansan, Santee, Hartington, Cedar Bluffs and Nickerson as applied to till units is in doubt. New formal names for tills are not proposed here. Instead, I urge restraint in such action being taken until the correlations presented here are checked and further information concerning the geographic distribution and relationships of the tills is gathered--especially the relationship of tills at Hartford, South Dakota; Harrison County, Iowa and Guthrie County, Iowa, with those in Nebraska.

Perhaps of greater importance is the problem of what is to be considered Nebraskan in the study area. The correlations presented in this report indicate Shimek (1909) erred when he correlated the till above Florence, Nebraska (his Nebraskan Till) with the lower till (pre-Kansan) near Afton, Iowa. It is clear from his report that he intended to apply a formal name to the pre-Kansan Till. Thus, the two tills near Afton, Iowa were thought to be Kansan Till over Nebraskan Till. Even though the tills near Afton, Iowa, are considered Kansan over Nebraskan, the problem of what is Nebraskan remains because correlations presented in Figure 2-9 indicate the Elk Creek Till (early Nebraskan, Reed and

Dreeszen, 1965) is older than the pre-Kansan or Nebraskan Till near Afton. Furthermore, other evidence, to be presented in Chapter 3, suggests the entire Nebraskan sequence (of Reed and Dreeszen, 1965) in eastern Nebraska is older than the pre-Kansan or Nebraskan Till near Afton, Iowa.

Only five tills were identified in Nebraska during this study as compared to seven tills differentiated here by Reed and Dreeszen (1965--see Fig. 206). It is not surprising a smaller number of tills was detected in my study because the presence of the Iowa Point Till (see Fig. 2-6) was based on speculation of the Fullerton Formation being related to a glaciation that reached Nebraska and/or Kansas (personal communication, Reed and Dreeszen, 1970). Also, an area of geomorphically young appearing glacial material in northeastern Nebraska was not sampled during my study.

It may be problems in terminology of glacial tills in Nebraska, as outlined above, are partially a result of some incorrect correlations made in an attempt to relate evidence obtained from extensive subsurface investigation to surface exposures. These kinds of correlations were attempted by Reed and Dreeszen (1965) in order to demonstrate on surface outcrops stratigraphic relationships they interpreted from regional subsurface information.

Comments Concerning the Formation of Till in the Study Area.

Although a detailed discussion of glaciology is beyond the scope of this paper and the competence of the author, several phenomena observed during the course of this study

may yield some light on the subject.

The correlations shown schematically in Figure 2-9 rely on the assumption that the heavy mineral and pebble composition of till sheets in the study area (especially eastern Nebraska) remain fairly consistent. A question that arises is how is it possible for a till sheet to maintain a compositional uniformity over such a large area?

An impression held by many geologists is that glaciers plough, grind and thoroughly mix the materials in their path (especially unconsolidated materials) resulting in a large lateral variation in till composition. Flint (1949, p. 189) states "It is not even possible to correlate sections of till throughout a wide region on a basis of lithologic character, because the composition of a till changes with changing composition of the underlying bedrock." This undoubtedly true where glaciers are eroding. But, were the ancient ice sheets eroding near their periphery after having crossed hundreds of miles of terrain and extending more than 1,500 miles farther into temperate latitudes than their modern-day counterparts?

There are indications in the study area the ancient glaciers, except possibly for the one that deposited the Elk Creek Till, were mainly agents of deposition. The most obvious evidence for glaciers being considered agents of deposition is preserved oxidation and leached horizons, paleosols, accretion gleys, boulder bands, and humic horizons or "peat" beds between tills. Indeed, historically differentiation and correlation of tills commonly has been based on widespread preservation of these features.

The composition of till units offers further evidence of a lack of wholesale erosion in the study area by most of these ice sheets. Except for the Elk Creek Till, the tills contain only about 5 to 10 percent locally derived bedrock. The locally derived pebbles are generally very angular whereas the others are moderately to well rounded and commonly polished. Also, at the Hartford, South Dakota Site the basal till rests on Sioux Quartzite (Precambrian). However, as can be seen in Appendix G, this till is no richer in quartzite pebbles than tills in southeastern Nebraska and western Iowa.

The glacier that deposited the Elk Creek Till appears to have been a more active agent of local erosion than the others. About 50 percent of the pebbles in the Elk Creek Till were derived from local bedrock. These locally derived pebbles are very angular and generally are considerably larger in size than pebbles from distant sources. The relatively large compositional variation of the Elk Creek Till may be due to local erosion by the glacier that deposited it.

It may be the high proportion of locally derived pebbles in the Elk Creek Till can be considered evidence indicating the glacier that deposited this till was the first to enter the study area. Therefore, the relatively high percentage of locally derived sedimentary pebbles in the Elk Creek Till may be due to the availability of large amounts of previously loosened local rocks rather than extensive local erosion by the glacier.

Although the glaciations succeeding the Elk Creek glaciation apparently were more depositional than erosional, some

erosion did occur locally. The basal few feet of the upper till at the City Wide Rock Quarry bears a compositional imprint of the middle till and the basal few feet of the middle till bears a compositional imprint of the lower (see Appendix G and Figure 2-5). This is only true of the pebbles, however, and not the heavy minerals(see Figures 2-4 and 2-5). Also superimposed tills at other sites did not show this compositional imprint. These observations may indicate a gravel lag formed on the older tills in the City Wide Area and was later incorporated into the basal part of the overlying till.

Two alternate mechanisms that might account for the change in the pebble composition within a till are presented by Flint (1971) and Dort (1965). Flint (1971, p. 182) states, "In some districts till is predominantly local at its base, with the proportion of foreign elements increasing upward. This suggests the possibility that the glacier first stirred up the local regolith, mixed it with drift, and redeposited much of it nearby; the redeposited layer protected the ground from further erosion and permitted deposition of far-traveled drift. Such a sequence should be related only to the peripheral part of a former glacier."

Dort (1965) noted compositional differences in Kansan till overlying Nebraskan gravels on a striated limestone surface in northeastern Kansas. Bayne, (1968) noted these gravels consist of chert and limestone containing few northern derived erratics. The pebbles in the lower part of the Kansan till consist mainly of limestone and dolomite with some shale and chert. This pebble composition changes

abruptly to one containing numerous pebbles, cobbles and boulders of igneous and metamorphic rocks. Dort believed the high sedimentary pebble content in the basal till was a result of incorporation of local bedrock by clean glacier ice formed by direct precipitation at the ice front. Later, when the ice that formed in Canada and rich in crystalline rocks reached the area, the composition of the till changed abruptly to one containing numerous igneous and metamorphic pebbles.

It is my opinion that the mechanism proposed by Flint (1971) best explains the change in pebble composition within a till. My field and laboratory observations lead me to believe that by the time the ice sheets reached the study area (southeastern South Dakota, western Iowa, and eastern Nebraska) they were virtually loaded. Therefore, they were unable to erode and incorporate large amounts of the local bedrock. Thus, their compositional imprints were set by the time they reached the study area and till sheets exhibiting compositional uniformity over large areas were deposited.

Observations of White (1972) support these conclusions. He observed that stratigraphic cover surrounding the Canadian shield crops out in concentric zones. These concentric zones expose successively younger strata away from the edge of the exposed shield. White notes Mesozoic or Tertiary strata usually occupy only the most peripheral locations, where glacial erosion was nil. Most of the bedrock of northwestern Iowa, southwestern Minnesota, eastern South Dakota and eastern

Nebraska is upper Cretaceous in age. Some Tertiary rocks occur in northeastern Nebraska.

Except at the Hartford, South Dakota and Harrison County, Iowa sites, the tills at the multiple till sections studied become progressively richer in hornblende and nonsedimentary pebbles and poorer in opaque minerals upward (Figure 2-7). This trend may indicate a progressive stripping of sedimentary rock cover from the crystalline rocks of the Canadian Shield and burial of sedimentary rocks to the south by drift. The composition of the tills at Hartford, South Dakota, and Harrison County, Iowa, indicate this trend may have been reversed one or more times during successively younger glaciations. This may have been accomplished by deposition from lobes having different sources or, perhaps, by a shifting of the center of ice accumulation during and between glacial advances.

III RE-EVALUATION OF THE CLASSIFICATION OF EARLY AND MIDDLE PLEISTOCENE DEPOSITS.

Fission-track ages indicate ashes previously termed Pearlette consist of four significantly different ages of ash--about 0.61 m.y., 0.74 m.y., 1.21 m.y., and 1.97 m.y. During the development of the classification of the Pleistocene deposits in Nebraska and adjoining areas the "Pearlette Ash" was used as a marker bed of late Kansan age. Consequently, regional correlations based on the premise of a single volcanic ash, when in reality there are four ashes with significantly diverse ages, would lead to errors in the classification devised and currently used for Pleistocene deposits in Nebraska and adjoining areas.

New correlations of tills based on heavy mineral and pebble type data indicate several generally accepted till correlations are erroneous. Some of these correlations have been of fundamental importance in the development of the classification framework of early and medial Pleistocene deposits in North America.

These new till correlations indicate that: (1) the type sections or areas of the Santee Till (Illinoian, Reed and Dreeszen, 1965), Cedar Bluffs Till (medial Kansan, Reed and Dreeszen, 1965), Nickerson Till (early Kansan, Reed and Dreeszen, 1965), Kansan Till (Bain, 1896 and Chamberlin, 1896) and Nebraskan Till (Shimek, 1909) are parts of the same till sheet; (2) the type sections or areas of the Hartington Till (Wisconsinan, Reed and Dreeszen, 1965) and the pre-Kansan Till (Bain,

1896 and Chamberlin, 1896) are parts of the same till sheet.

If the new correlations are correct, several formally designated till names having separate age assignments have been applied to the same till sheet (see Fig. 3-1). This in itself implies serious problems in local till terminology. These problems become regional and even hemispheric when one considers that the terms Kansan, Aftonian, and Nebraskan are used as stage names in North America and beyond.

The problems with the current classification and nomenclature of both glacial and nonglacial Pleistocene deposits in Nebraska and adjoining areas are compounded when the volcanic ash dates and till correlations are considered together.

Near David City, Nebraska, (Figs. 2-1 and 3-1, loc. 8) a volcanic ash dated at 1.2 m.y. occurs near the top of a thick sequence of silt and clay assigned to the Fullerton Formation (late Nebraskan, Dreeszen, 1970). This silt-clay sequence is overlain by two tills assigned a Kansan age by Dreeszen (1970). The lower of the tills correlates compositionally with the upper till (Kansan) near Afton, Iowa (see Fig. 3-1).

The ash near David City, Nebraska, correlates with another ash deposit exposed near Coleridge, Nebraska, (Figs. 2-1 and 3-1, loc. 6). This correlation is based on the similarity of fission-track ages and of chemical compositions (see Table 1-1 and Fig. 1-4). I have collectively termed these ashes the Coleridge ash.

The Coleridge ash near Coleridge, Nebraska, occurs near the top of a silt sequence believed to be the Fullerton

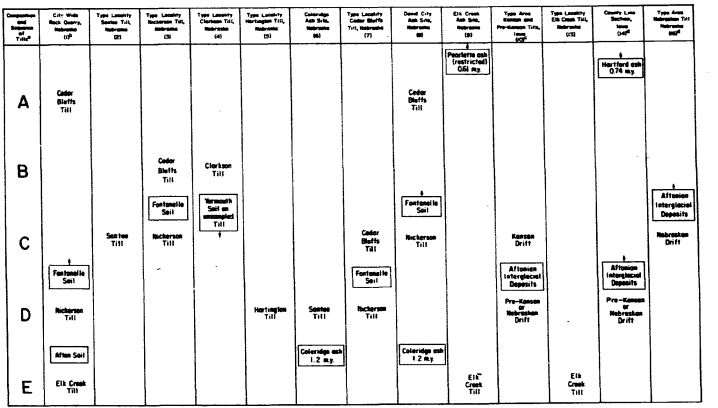


Figure 3-1: Till correlations based on heavy mineral and pebble type data. Till names show previous correlations. Position of till names with respect to left hand column illustrates the correlations of tills based on heavy mineral and pebble type data (this study). Except for localities 10, 14, and 16, terminology is from Reed and Dreeszen, 1965 (see Figure 2-6 for terminology and age assignments). Volcanic ash terminology and dates from this study (see Table 1-1). Position of ash based on interpretations of stratigraphic relationships, pebble and heavy mineral composition and age data.

Formation. This ash is overlain by a till that correlates compositionally with the lower till (pre-Kansan) near Afton, Iowa and a till assigned an early Kansan age in eastern Nebraska (Reed and others, 1966).

The correlations outlined above indicate the Coleridge ash occurs near the top of sediments assigned a late Nebraskan age in Nebraska and below a till correlated with both the early Kansan till in Nebraska and the pre-Kansan till near Afton, Iowa. If these correlations are correct, the Nebraskan sequence of Reed and Dreeszen (1965) is older than the pre-Kansan till (of Bain, 1896 and Chamberlin, 1896) near Afton, Iowa, and the pre-Kansan till near Afton is younger than about 1.2 m.y. Most of Reed and Dreeszen's Nebraskan sequence is older than this.

The Coleridge ash also occurs at the top of the Sappa Formation (late Kansan, Reed and Dreeszen, 1965) at its type locality (Fig. 1-1, loc. 8). The relationships of the Coleridge ash to glacial and nonglacial sediments at Coleridge and David City indicate the Sappa Formation at its type locality is older than late Kansan and is probably late Nebraskan in age following Reed and Dreeszen's (1965) classification (Fig. 2-6).

The presence of Illinoian till in northeastern Nebraska (Condra and Reed, 1950) and southeastern South Dakota (Flint, 1955) was based largely on the occurrences of till overlying volcanic ash near Coleridge, Nebraska, and Hartford, South Dakota (Fig. 2-1, locs. 6 and 12, respectively). At the

time these tills were described they were assigned an Illinoian age because it was then believed only one age of volcanic ash was present in the Central Plains--the Pearlette Ash of late Kansan age. Therefore, it is understandable why till overlying volcanic ash like at Coleridge and Hartford was assigned a post-Kansan age. However, it now appears the ash deposit at Hartford is 0.74 m.y. old and that at Coleridge is 1.2 m.y. old. These ashes are also chemically distinct (see Fig. 1-4). Since these ashes are not the same, there is no need to assume the tills are the same. In fact, the heavy minerals and pebble counts indicate they are not. There is furthermore no need to assume an Illinoian age for a till overlying volcanic ash. Because ash deposits ranging in age from early to middle Pleistocene occur in the central Plains, a till overlying an ash may be as old as Nebraskan.

The Borchers Ranch ash location (Fig. 1-1, loc. 11) is the type locality of both the Meade Formation (Frye and Leonard, 1952) and the more restricted Crooked Creek Formation (Hibbard, 1949). Both formations were considered to be late Kansas in age. The ash and associated sediments at this locality were also correlated with the Sappa Formation of late Kansan age by the Kansas Geological Survey (Zeller, 1968). The Borchers ash, however, is about 2.0 m.y. old (see Table 1-1) and is older than the Coleridge ash (1.2 m.y.) at the type locality of the Sappa Formation (Fig. 1-1, loc. 8). The Sappa at its type locality has already been shown to be much older than late Kansan and is probably equivalent in age to

the Fullerton Formation (Late Nebraskan, Reed & Dreeszen, 1965). Because the Borchers ash is about 0.8 m.y. older than the Coleridge ash, the Meade and Crooked Creek Formations are, at least in part, early Nebraskan in age (following the terminology of Reed and Dreeszen, 1965).

The Borchers ash is overlain by a vertebrate fauna (Borchers fauna of Hibbard) which Hibbard (1972) considers to be Aftonian in age. This ash is underlain by sand and gravel assigned to the Stump Arroyo Member of the Crooked Creek Formation (Hibbard, 1949 - see Appendix F). Hibbard (written communication, March 6, 1973) considers the Stump Arroyo gravel to be the same age as the Angell Member of the Ballard Formation (late Pliocene or earliest Pleistocene, Hibbard, 1972). He now considers the Angell Member to have been deposited during, or after, Alpine glaciation, but prior to the Nebraskan glaciation. If Hibbard's interpretations are correct, the dates of 1.9±0.2 m.y. (Fission-track on zircon, Naeser and others, 1971) and 1.97±0.25 m.y. (fission track on glass, this study) may approximate the initiation of continental glaciation in the Central Plains and also may approximate the age of boundary between sediments considered Pleistocene and Pliocene.

As they stand, the correlations of tills and dates on volcanic ashes presented in this report indicate several presently accepted correlations are erroneous and much of the terminology used to communicate information about early and medial Pleistocene deposits in Nebraska and adjoining areas

may not be useful. The terms Nebraskan Till, Kansan Till, Nickerson Till, Cedar Bluffs Till, Santee Till, Sappa Formation, Meade Formation, and Crooked Creek Formation, for example, need to be redefined.

The till correlations, furthermore, suggest in some cases the terms Afton and Fontanelle have been applied to the same paleosol or to paleosols of various ages (see Fig. 3-1). The term Afton has long been applied to the paleosol occurring between the Kansan and pre-Kansan tills in the Afton, Iowa area. At the City Wide Quarry in Nebraska (Fig. 3-1, loc. 1) the term Afton has been applied to a paleosol occurring at the top of Reed and Dreeszen's Nebraskan sequence and underlying a till assigned an early Kansan age and correlates with the pre-Kansan till of the Afton, Iowa, area. These relationships indicate the term Afton has been misapplied in Nebraska. The till correlations also indicate the term Fontanelle Soil (Reed and Dreeszen, 1965) has been applied to several different ages of paleosols, including the Afton (see Figure 3-1).

If the deposits termed Nebraskan Till, Afton, and Kansan Till at their type localities need redefinition; then stage names derived from them--Nebraskan, Aftonian, Kansan-need to be redefined. Such a redefinition, of course, has many implications because these stage names are applied to Pleistocene deposits throughout North America. To illustrate this need for redefinition, it is necessary to briefly trace the use of the terms Nebraskan, Aftonian, and Kansan.

Until about 1870 it was thought only one drift sheet was present in the United States. At about this time evidence for two glaciations was published by several workers (Worthen, 1868; White, 1870; Orton, 1871; Winchell, 1872; Orton, 1873; Winchell, 1874; and McGee, 1878).

McGee (1878) identified two tills in northeastern Iowa and referred to them only as upper and lower. In 1893, Chamberlin recognized two drifts in the Afton Junction - Thayer region of Iowa and correlated these drifts with McGee"s upper and lower drifts respectively (Fig. 3-2). Chamberlin (1893) named the lower drift Kansas Formation because he believed this was the drift sheet that extended into northeastern Kansas. He named the upper drift East Iowa.

Chamberlin (1894) used the term Kansan stage for the first glacial epoch and East Iowan stage for the second. He recognized that an older glacial epoch may exist, but at that time its presence was theoretical. In 1895 Chamberlin applied the name Aftonian interglacial stage to the gravel, peat, and sand occurring between his East Iowan and Kansan drifts near Afton, Iowa.

Bain (1896) studied the drift deposits in western Iowa and concluded the upper drift at Afton was the one that elsewhere was recognized as Kansan. Chamberlin (1896), after examining Bain's evidence, concurred with his conclusion. Thus, the lower drift (Chamberlin's Kansan drift) at Afton became pre-Kansan and the upper drift (Chamberlin's East Iowan) became Kansan. The sequence near Afton then came to be known

Till Composition and Sequence	Type Area Kansan and Pre-Kansan Drift, Afton, Iowa			Type Area Nebraskan Drift, Florence, Nebraska	Type Area of Several Tills, Eastern Nebraska
This Study[a]	Chamberlin 1893	Bain, 1896 and Chamberlin, 1896	Shimek, 1909	Shimek, 1909	Reed and Dreeszen, 1965
C	East Iowa Drift	Kansan Drift	Kansan Drift	Nebraskan Drift	Four named tills assigned ages ranging from Wisconsinan thru Kansan
D	Kansan Drift	Pre-Kansan Drift	Nebraskan Drift		
E	a. Letters refer to till composition as shown in Figure 2-7 and 2-8.				(Coleridge ash-1.2 my.) Nebraskan Sequence including two named tills

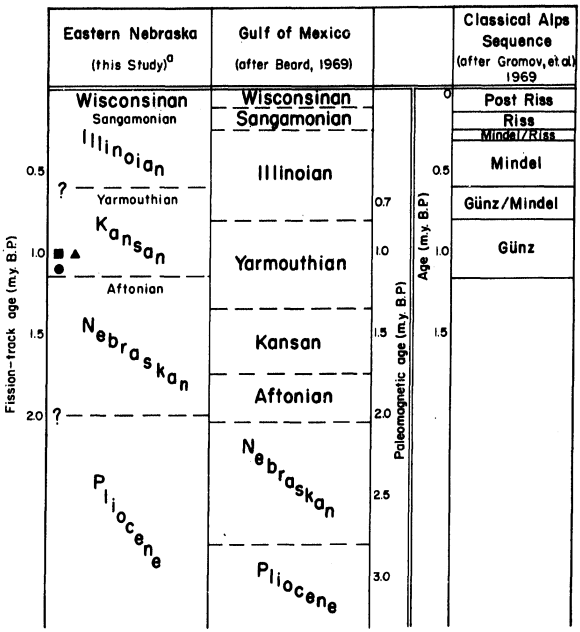
Figure 3-2: Correlations of some Early and Middle Pleistocene tills in their type areas.

as Kansan drift over Aftonian interglacial deposits over pre-Kansas drift.

Finally, Shimek (1909) proposed the name Nebraskan for Bain's pre-Kansan drift. The type area designated for the Nebraskan drift was in the Missouri River bluffs in South Omaha, and above Florence, Nebraska, and 4 miles north of Council Bluffs, Iowa. Consequently, the deposits in the Afton, Iowa, area then came to be known as Kansan drift over Aftonian interglacial deposits over Nebraskan drift. Nebraskan became the stage name for the first glacial episode and Kansan became the stage name for the second glacial episode.

As shown in Figure 3-2 till correlations based on heavy mineral and pebble type data suggest Shimek's (1909) Nebraskan Till correlates with the upper till (Kansan) near Afton, Iowa rather than the lower till (pre-Kansan). Thus, it appears the terms Kansan and Nebraskan were applied to the same till sheet. Even if the terms Kansan and Nebraskan are restricted to their usage near Afton, Iowa, correlations presented in this report indicate all of Reed and Dreeszen's (1965) Nebraskan sequence is older than the Nebraskan Till (or pre-Kansan) near Afton, Iowa (see Fig. 3-2).

The usefulness of the terms Kansan and Nebraskan as stage names becomes more confusing when the inferred chronologies for the Central Plains (this study) and Gulf of Mexico (Beard, 1969) are compared. As illustrated in Figure 3-3, this comparison indicates the term Nebraskan has been applied to sediments ranging in age from about 1 m.y. to about 3 m.y. and



a. Terminology after Reed and Dreeszen, 1965 (see Figure 2-6).
● Pre-Kansan Drift of Bain (1896) and Chamberlin (1896).
■ Kansan Drift of Bain (1896).
▲ Nebraskan Drift of Shimek (1909).

Figure 3-3: Comparison of some Pleistocene Chronologies.

the term Kansan to sediments ranging in age from about 0.6 m.y. to about 1.7 m.y.

During the development of the classification of early Pleistocene deposits in North America it was believed each glacial stage was represented by single drift. Over the last decade much evidence has been presented which shows the glacial history of the early Pleistocene is probably as complex as that of the Wisconsinan. In view of this complexity of early Pleistocene glaciations, the restriction of the stage names Nebraskan, Aftonian, and Kansan to their original usage for the tills and interglacial deposits near Afton, Iowa, would serve no useful purpose. Indeed, such a restriction would probably necessitate abandoning these terms as stage names.

Any redefinition of the terms Nebraskan, Aftonian, and Kansan must take in account that many, if not most, students of the Pleistocene in North America have the concept of Nebraskan as the first major episode of Pleistocene continental glaciation, the Aftonian as the first interglacial episode and Kansan as the second episode of continental glaciation. Indeed, this concept was probably followed by Beard (1969) in naming the lowermost Pleistocene cold cycle detected in the Gulf of Mexico sediments Nebraskan and the next younger cold cycle Kansan.

Reexamination and redefinition of these stage names must recognize the problems involved with defining the Pliocene-Pleistocene boundary. The Calabrian stage of southern Italy was originally assigned to the Pliocene by Gignoux

(1910) and was reassigned to the Pleistocene by the XVIIIth International Geological Congress (London, 1948). In 1965 the base of the Calabrian stage was accepted as the base of the Pleistocene by the General Assembly of the 7th INQUA Congress.

Data on rates of sedimentation presented by Selli (1967) and paleomagnetic data presented by Nakagawa and others (1970) indicate that the base of the Calabrian is about 1.8 m.y. old. This date is about the same as that presented for the base of Kansan in the Gulf of Mexico (Beard, 1969). The correlation of the basal Calabrian with the base of Beard's Kansas in the Gulf of Mexico is supported by faunal evidence presented by Poag (1972).

The record of early Pleistocene events in the Central U.S.A. must certainly be closely related to the depositional history of sediments in the northern Gulf of Mexico. Because the record of these events is probably more nearly complete there than in any part of the glaciated region, the chronology of glacial and interglacial stages can probably most accurately be determined from detailed studies of the sediments in the northern Gulf of Mexico.

If the base of the Calabrian is generally accepted as the base of the Pleistocene and if the correlations between Italy and the Gulf of Mexico are correct, then Beard's data indicate the Pleistocene in the northern Gulf of Mexico--and presumably the Central U.S.A.--would consist of three glacial stages, not four (see Fig. 3-3). Beard's (1969) Nebraskan

would become pre-Pleistocene and the base of his Kansan would be basal Pleistocene.

Restricting the base of the Pleistocene to the base of the Calabrian--about 1.8 m.y. old--would permit retaining the term Nebraskan and Kansan in the concept of first and second Pleistocene glacial stages respectively. However, if Beard's (1969) paleotemperature curve is correct, there may be only three glacial stages younger than about 1.8 m.y. (base of the Calabrian), the concept of four Pleistocene glacial stages currently adhered to in the Central U.S.A. would have to be adjusted to a three stage concept.

I accept the Calabrian Stage as the base of the Pleistocene as recommended by the 18th International Geological Congress (London, 1948) and accepted by the General Assembly of the 7th INQUA Congress (Denver, 1965).

It is my opinion that the term Nebraskan should be used in the concept of the first Pleistocene continental glaciation younger than basal Calabrian (i.e. younger than about 1.8 m.y.) and the term Kansan for the second. The age boundaries of the glacial and interglacial stages will probably have to be established by means of faunal, paleomagnetic, and radiometric studies of the more complete sedimentary records preserved in the Gulf of Mexico. These boundaries can then hopefully be carried into the incomplete continental sequence by means of radiometric, paleomagnetic, and fauna studies.

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APPENDIX A

A Brief Outline of the Development of the Major Divisions of the Pleistocene Classification of North America.

Prior to the concept of a glacial origin of drift, it was believed that surficial deposits of boulder clay, sand, gravel, and silt were formed by icebergs dropping foreign material on the surface during a single period of submergence beneath the sea. These deposits were collectively termed drift. Evidence suggesting that there were at least two periods of drift deposition was first presented in the 1860's, before the glacial origin of drift gained general acceptance in North America.

1868 - Worthen, A. H., describes the presence of deposits of "...dark blue or black mud, containing branches of trees and sometimes trees of large size.", sandwiched by drift deposits. (Geology of Jackson County: Geological Survey of Illinois, vol. 3, Chapter IV, p. 75).

1870 - White, C. A., states that the drift deposits of Iowa are glacial in origin. (Report of the Geological Survey of the State of Iowa: Iowa Geol. Survey, vol. 1, p. 82-100).

1871 - Orton, E., reports the presence of vegetable remains overlain and underlain by drift deposits. He proposed that there were two periods of submergence with drift deposition separated by a period of emergence during which the vegetable deposits formed. (Report on the Geology of Montgomery County: Survey of Ohio, Part III, p. 166-167).

1872 - Winchell, N. H., noted the presence of vegetable deposits between two glacial drifts in Minnesota. He believed the vegetable deposits to be interglacial in age. (The Geological and Natural History Survey of Minnesota: 1st. Annual Report of the Minnesota Geological Survey, p. 61).

1878 - McGee, W. J., recognized two tills in northeastern Iowa and pointed out this duality as opposed to the single glaciation previously supposed. In his opinion the interval represented by the forest bed (interglacial) was enormous in length. These two drifts were referred to only as Upper and Lower. (On the Relative Positions of Forest Bed and Associated Drift Formations in Northeastern Iowa: Am. Jour. Sci., 3rd series, vol. XV, pp. 339-341).

1893 - Chamberlin, T. C., began the practice of giving geographic names to the various ages of Pleistocene drift. He recognized two tills in the Afton Junction-Thayer region of Iowa and correlated these two drifts with McGee's Upper and Lower drifts respectively. The lower till was named Kansan becuase it was recognized that a till sheet extended into northeastern Kansas and it was thought that the lower till of the Afton-Thayer region correlated with it. The upper till was termed East Iowan. (Review of the Ice Age at the World's Congress on Geology: Am. Geologist, vol. 12, p. 223-231).

1894 - Chamberlin, T. C., published his classification of North American glacial deposits in which the names Kansan, East Iowan, and East Wisconsin were applied to both the glacial deposits from oldest to youngest and to the glacial stages. No names were applied to the interglacials. (Glacial Phenomena of North America: in Geikie, The Great Ice Age, 3rd edition, p. 724-775.

1895 - Upham, W., suggested that the names East Iowan and East Wisconsin be shortened to Iowa and Wisconsin (Climatic conditions shown by North American interglacial deposits: The American Geologist, vol. 15, p. 56).

- Chamberlin, T. C., accepted Upham's suggestion and at this time applied the name Aftonian (after Afton, Iowa) to the gravel, peat, and other interglacial deposits. So, his classification of the Pleistocene became:

Wisconsin Stage
Toronto interglacial deposits
Iowan Stage
Aftonian Interglacial
Kansan Stage

(The Classification of American glacial deposits: Jour. of Geol., vol. 3, pp. 270-277).

- Dawson, G. M., named a supposed drift in western Canada the Albertan and correlated it as older than the drift below the forest bed of northeastern Iowa which in turn Chamberlin and McGee correlated with the lower or Kansan drift at Afton, Iowa. Thus, the Albertan was considered as pre-Kansan. (Note on the glacial deposits of southwestern Alberta: Jour. of Geology, vol. 3, pp. 507-511).

1896 - Bain, H. F., reported that "In short, the upper drift at Afton was found to be the same as that which was elsewhere recognized as Kansan, and a still lower pre-Kansan drift sheet was recognized." He also postulated that this pre-Kansan drift was the same as Dawson's

Albertan drift (Relations of the Wisconsin and Kansan Drift Sheets in Central Iowa, and Related Phenomena: Iowa Geol. Sur., Vol. 6, pp. 464).

- Chamberlin, T. C., concurred with Bain's interpretation and "This places the Aftonian beds below the Kansan series instead of above them." (Editorial, Jour. Geol., vol. 4, pp. 872-876). In the same editorial he gives the Pleistocene succession as;

Wisconsin till sheets
Interglacial deposits--Toronto?
Iowan till sheet
Interglacial deposits
Illinoian till sheet (Leverett)
Interglacial deposits (Buchanan of Calvin)
Kansan Till sheet
Aftonian beds, Interglacial
Albertan Drift Sheet (Dawson)

1898 - Leverett, F., intorduced the terms Yarmouth, Sangamon, and Peorian. The Yarmouth was applied to the soil and weathered zone at the junction of the Illinoian and Kansan till sheets in the region of overlap. Sangamon was applied to the soil horizon between the Illinoian till sheet and the Iowan loess. Peorian was applied to the weathered zone at the contact between the Iowan till and the Wisconsin till near Peoria, Illinois. (The weathered zone (Sangamon) between the Iowan loess and Illinoian Till Sheet: Journal of Geology, vol. 6, p. 171-181).

1899 - Leverett, F., presented the following classification of Pleistocene deposits: (The Illinois glacial lobe: U. S. Geol. Survey Mon. 38, 817 pp.)

Lake Chicago Stages
Late Wisconsin morainic drift
unnamed interval of shifting ice lobes
Early Wisconsin drift (morainic)
Peorian
Iowan drift and main loess deposits
Sangamon interval
Illinoian drift
Yarmouth interval
Kansan drift
Aftonian interval
Oldest drift sheet (Albertan of Dawson and sub-Aftonian or pre-Kansan of Chamberlin)

1909 - Shimek, B., proposed the name Nebraskan for the oldest drift - Chamberlin's pre-Kansan or pre-Aftonian. (Aftonian Sands and Gravels in Western Iowa: Geol. Soc. America Bull., vol. 20, pp. 399-408). He states (P. 408):

"The terms pre-Kansan and sub-Aftonian have been used merely to designate the position of this drift sheet (the lower drift at Afton, Iowa): the name Albertan was originally applied to a deposit which can not be correlated with this drift, and which is not now regarded as glacial; and the doubtful Jerseyan can not be connected with the sheet here discussed. This leaves it without a name, and in view of this fact, and of the wide distribution of this formation, the name Nebraskan is proposed for it. The type exposures are located in the Missouri bluffs in South Omaha and above Florence, Nebraska, and 4 miles north of Council Bluffs, Iowa. The name Nebraskan was suggested to the writer by Professor Calvin."

1909 - Leverett, F., questioned the existence of the Iowan drift. He felt that both the 'Iowan' of northeastern Iowa and the Kansan exhibited similar topography and weathering. He studied the Iowan area and concluded that it was no different from the weathered Kansan drift (Weathering and erosion as time measures: Am. Jour. Sci., 4th ser., vol. 27, pp. 349-368).

1910 - Chamberlin, T. C., in reference to Leverett's proposal stated "It is appropriate here to urge restraint, patience, and equipoise, for the distinguishing phenomena, while pronounced and peculiar, are subtle in their gradations and singularly puzzling." (Review of the Comparison of North American and European Glacial Deposits, Jour. Geol., vol. 18, pp. 470-474).

- Shimek introduces the name Loveland for the reddish silt-clay above the Kansan drift. (The Pleistocene of the Missouri Valley: Sci., vol. 31, pp. 75-76).

1911 - Calvin, S., vigorously disagreed with Leverett's (1909) proposal and defended the Iowan. He pointed out that in the earlier discussions of the Pleistocene deposits of northeastern Iowa it was assumed that there were only two drift sheets in that region, named by McGee the Upper Till and the Lower Till and later by Chamberlin the East Iowan and Kansan tills respectively. Confusion arose when it was discovered that there are three drift sheets and not two only in McGee's area. (The Iowan Drift: Jour. Geol., vol. 19, pp. 577-602).

1913 - Leverett, F., restated that the Iowan might be a late glaciation of the Illinoian stage. (Iowan drift: Abst., Geol. Soc. American Bull., vol. 24, pp. 698-699).

1915 - Alden, W. C. and Leighton, M. M., reviewed the Iowan problem in cooperation with the USGS in an attempt to

resolve the controversy. They state that "It is a pleasure to report that the conclusion has been reached that there is what seems to the writers to be good evidence of the presence of a post-Kansan drift sheet in northeastern Iowa and that this drift appears to be older than the Wisconsin and younger than the Illinoian drift. The writers are, therefore, in the main in agreement with the late State Geologist, Dr. Samuel Calvin, in regard to the Iowan drift. There is, therefore, warrant for continued use of Iowan drift and Iowan stage of glaciation as major subdivisions of the Pleistocene classification." (The Iowan drift, a review of the evidences of the Iowan stage of glaciation: Iowa Geol. Survey, vol. 26, pp. 49-212).

1915 - Carman, J. E., published a report on the Pleistocene geology of northwestern Iowa in which he described and mapped the area west of the Wisconsin moraine as Kansan. For a time, however, he felt that in this area there was a drift younger than the Kansan but older than the Peorian (The Pleistocene Geology of Northwestern Iowa: Iowa Geological Survey Annual Report, vol. 26, p. 234-308).

1924 - Kay, G. F., concludes that: (a) evidence indicates that both the Kansan and Nebraskan till sheets with the Aftonian interval extend well into the State of Nebraska; (b) in western Iowa it has not been possible to differentiate the Kansan and Nebraskan on the basis of color, lithology, weathering or texture; (c) the gravels of the Afton, Iowa, area are not thought to represent a distinctive stratigraphic unit separating the Kansan and Nebraskan tills but are in reality lenses within a single till or perhaps in two tills and if the latter is true, they are not useful for differentiating the tills; and (d) the volcanic ash at the Harrison County, Iowa, exposure is not Aftonian in age as proposed by Shimek, but is of the same age as the Loveland. Also, the Loveland is aeolian in origin instead of fluvio-glacial as proposed by Shimek. (Recent Studies of the Pleistocene in Western Iowa: Abst., Geol. Soc. America Bull., vol. 35, pp. 71-73).

1926 - Sardeson, F. W., goes on record against the presence of an Iowan drift sheet in northeastern Iowa and concludes that only four of the five generally recognized glacial stages should be included in the classification of the Pleistocene. (Four Stage Glacial Epoch: Pan-American Geologist, vol. 46, pp. 175-188).

- Leverett, F., argues that there is a post-Kansan drift in northeastern Iowa, the Iowan, but believes that this drift is correlative with a late phase of the Illinoian

stage glaciation. He too favored the four stage concept of glaciation. (The Pleistocene Glacial Stages: were there more than four?: Proc. Am. Philosophical Soc., vol. 65, no. 2).

1928 - Kay, G. F., states that "The Loveland loess has now been established by stratigraphic methods as being much younger than the Illinoian glacial drift and older than the Iowan glacial drift." (Loveland Loess: Post-Illinoian, Pre-Iowan in Age: Science, vol. 48, pp. 482-483).

- Kay, G. F., made additional statements in support of the Iowan being a distinct glacial stage from the Illinoian. He states that:

> "The strongest of several arguments in favor of a long interval between the Illinoian and Iowan glacial stages are the occurrence of a gumbotil on the Illinoian in contrast to no gumbotil on the Iowan, and the leached Loveland loess, which is post-Illinoian gumbotil, pre-Iowan in age.
>
> The relative ages of the Iowan and Illinoian glacial stages would seem to have been established, and hence five glacial stages and four interglacial stages must continue to be given a place in the classification of the North American glacial deposits." (The Relative Ages of the Iowan and Illinoian Drift Sheets: American Journal of Science, 5th series, vol. 16, pp. 497-518).

- Kay, G. F. and Apfel, E. T., present the classification of Pleistocene deposits recognized by the Iowa Geological Survey as:

Glacial Stages	Interglacial Stages
Wisconsin	
	Peorian
Iowan	
	Sangamon
Illinoian	
	Yarmouth
Kansan	
	Aftonian
Nebraskan	

The term Buchanan was still retained at that time for the interval between the Kansan and the Iowan. (The Pre-Illinoian Pleistocene Geology of Iowa: Special Report of the Iowa Geological Survey).

1929 - Kay, G. F., showed that the Iowan drift is much more closely allied with the Wisconsin than the Illinoian and suggested that the Iowan be placed as a substage of the Wisconsin glacial stage. (The relative age of the Iowan and Wisconsin drift sheets: Am. Jour. Sci., vol. 21, pp. 158-172).

1931 - Leighton, M. M., demonstrated that loess deposition was continuous from Iowan time until after-Early Wisconsin time and in addition that the Peorian interval was so short that it required its elimination as an interglacial stage. He went on to propose that since the Iowan cannot be recognized as a distinct glacial stage from the Wisconsin stage, that the former be included with the Wisconsin stage as its earliest substage. (The Peorian loess and the classification of the glacial drift sheets of the Mississippi Valley: Jour. Geol., vol. 38, pp. 45-53).

In this paper Leighton also proposed the following substage names for the Wisconsin.

Wisconsin		Hudsonian
		Quebecan
		Manitoban (Iowan)

1931 - Kay, G. F., proposed the following classification of the Pleistocene. (Classification and duration of the Pleistocene period: Geo. Soc. America Bull., vol. 42, pp. 425-466).

Period (system)	Epochs (series)	Ages (stages)	Substages
		(Recent)	
	Eldoran	Wisconsin	
		Peorian	
		Iowan	
Pleistocene	Centralian	Sangamon	
or		Illinoian	
Glacial	Ottumwan	Yarmouth	
		Kansan	
	Grandian	Aftonian	
		Nebraskan	

1932 - Leighton, M. M., proposes that both the Iowan & Peorian be included as substages of the Wisconsin (Elimination of the Peorian interglacial epoch from North American Classification: (abstract), Geol. Soc. American Bull., vol. 43, p. 176).

- Leighton, M. M., and Kay, G. F., jointly published a paper in which the following classification was proposed. (Eldoran Epoch of the Pleistocene Period; Geol. Soc. America Bull., vol. 44, pp. 669-674).

Period (system)	Epochs (series)	Ages (stages)	Substages
		Recent	
	Eldoran		Mankato
		Wisconsin	Cary
			Tazewell
Pleistocene			Iowan
or	Centralian	Sangamon	
		Illinoian	
Glacial			
	Ottumwan	Yarmouth	
		Kansan	
	Grandian	Aftonian	
		Nebraskan	

"The name Peorian will continue to be used in Iowa for the widespread loess which lies on the Iowan drift and around its border, and beneath the Mankato (Late Wisconsin) drift; and in Illinois for the widespread loess which lies above the Late Sangamon loess outside of the Tazewell drift. Within the border of the Tazewell drift the loess which immediately underlies it may be called Iowan, as originally proposed, and the loess which overlies it, the Tazewell loess. These two loesses are indistinguishable outside of the Tazewell drift border and compose the Peorian loess." p. 673.

About
1940 - Leverett held out a long time for the correlation of the Illinoian and Iowan but apparently before his death in 1943 he accepted the above classification "... thus leaving all American geologists essentially in agreement." Thwaites, E. T., Outline of Glacial Geology, University of Wisconsin, printed by Edwards Brothers, Inc., Ann Arbor, Michigan, 1946 and 1961, p. 72).

APPENDIX B

A BRIEF OUTLINE OF THE DEVELOPMENT OF THE PLEISTOCENE CLASSIFICATION IN NEBRASKA

1880 - Aughey, S., observed some Pleistocene exposures in eastern Nebraska and found evidence for two glacial advances separated by a retreat marked by the development of forest beds and soil (Physical Geography and Geology of Nebraska, Daily Republican Book and Job Office, pp. 252-309, Omaha, Nebraska).

1898 - Darton, N. H., presented a discussion on the character of the Early Pleistocene deposits in connection with a study of the water supply in southeastern Nebraska. He found that 'No order of succession has yet been determined for the glacial deposits.' (Underground Waters of a Portion of Southeastern Nebraska: U. S. Geol. Survey, Water Supply and Irrigation Paper, no. 12, pp. 21-33).

1899 - Todd, J. E., made the first rather extensive report on the Pleistocene deposits of Nebraska - especially those in northeastern Nebraska where he described a number of measured sections. (The Moraines of South Dakota and their Attendant Deposits: U. S. G. S. Bull. 158, pp. 56-81).

1903 - Barbour, E. H., states that the glacial drift of Nebraska belongs to the Kansan epoch. (Report of the State Geologist, Nebr. Geol. Survey, vol. 1, pp. 165-169).

1914 - Barbour, E. H., pointed out that materials of quite different age were known in the Pleistocene and called attention to the fact that the term "drift" had been applied in a too restricted sense in Nebraska. (A Phenomenon of the Kansan Drift in Nebraska: Jour. of Geol., vol. 22, no. 8, pp. 807-810).

1932 - Lugn, A. L., introduces five new formation names -- David City Formation (early Nebraskan), Holdrege Formation (Nebraskan), Fullerton Formation (Aftonian), Grand Island Formation (Kansan), and Upland Formation (Yarmouth). (Pleistocene formations of southern Nebraska: abstract, Geol. Soc. America Bull., vol. 43, p. 190).

1934 - Condra, G. E., outlined the Pleistocene framework of Nebraska as given below (Geological Phases of Soil Erosion Investigation and Control in Nebraska, Nebraska Geol. Survey Paper, no. 6, pp. 1-22).

Post Wisconsin

Wisconsin

Peorian

Iowan

Sangamon

Illinoian

Yarmouth

Kansan

Aftonian

Nebraskan

1935 - Lugn, A. L., presented a classification of the Pleistocene deposits of Nebraska. In this classification he followed Kay's 1931 classification and retained the Iowan stage rather than including it with the Wisconsinan as Kay and Leighton did in their 1933 revision of Kay's 1931 classification. Lugn states:

> "The writer feels that the advisability of includ-ind the Iowan as a sub-stage of the Wisconsin glacial stage has not been clearly established, and he is fully convinced that the Peorian age was of significant duration and should be retained in any satisfactory Pleistocene classification. The writer is also inclined to agree with Leverett that the new sub-stage names proposed for the Wisconsin (Kay and Leighton, 1933) were unnecessary."

In the same paper Lugn places the Pearlette volcanic ash in the Loveland Formation. (The Pleistocene geology of Nebraska: Nebraska Geological Survey, Bull. no. 10, 2nd series, pp. 1-213).

1943 - Condra, G. E., and Reed, E. C., present a classification of Pleistocene deposits which, unlike Lugn (1935), follows Leighton and Kay's 1931 classification by including the Iowan as a sub-stage of the Wisconsinan.

Condra and Reed also apply the terms Aftonian, Yarmouth, and Sangamon to the first, second, and third interglacial stages respectively. In addition, they recognize the presence of Pleistocene deposits older than Nebraskan till. (The Geological Section of Nebraska, Nebraska Geol. Survey, Bull. 14, pp. 1-82).

1945 - Schultz, B., and Stout, T. M., named and described a post-Peorian loess - the Bignell loess. (Pleistocene Loess Deposits of Nebraska, Am. Jour. Sci., May 1945).

1947 - Condra, G. E., Reed, E. C. and Gordon, E. D., followed the classification of Kay and Leighton (1933) recognizing the Iowan and Peorian as substages of the Wisconsin. Condra, Reed, and Gordon named the Crete Formation as "... a channel fill deposit which rests unconformably upon the Upland Formation (late Kansan)...and is believed to be Illinoian in age."

They also state "We have no Illinoian and probably no Wisconsin tills in Nebraska" (page 10). "The Illinoian ice sheet advanced into Illinois and southeastern Iowa but did not reach to Nebraska. It caused some erosion and deposited till, some subtill sand and gravel, and recessional sand and gravel in Illinois and Iowa and caused climatic changes accompanied by erosion and alluviation in Nebraska, but our state was too far from this ice sheet to be greatly influenced by the climatic change" (p. 23). They also cite evidence for the Pearlette Ash being pre-Loveland in age. (Correlation of the Pleistocene deposits of Nebraska: Nebr. Geol. Survey Bull. 15, pp. 1-73).

1948 - Reed, E. C., introduced the term Sappa Formation as a substitute for Lugn's Upland Formation. (Replacement name for the Upland Formation of Nebraska: abstract, Geol. Soc. America Bull., vol. 59, no. 12, pt. 2, p. 1346).

1948 - Frye, J. C., Swineford, A., and Leonard, B. A., adopted Kay's and Leighton's 1933 classification in their correlation studies of the Pleistocene deposits of the central Great Plains with the glacial section in Kansas, Nebraska, Iowa, and South Dakota. In this study, the Pearlette ash 'horizon' was the basis for correlation. (Correlation of Pleistocene deposits of the Central Great Plains with the glacial section: Jour. of Geology, vol. 56, no. 6, 1948).

1949 - Frye, J. C., and Leonard, B. A., described two tills separated by a soil in Doniphan County, Kansas. The lower till they interpreted as being Nebraskan in age and the upper one Kansan. Afton soil separating the tills. (Pleistocene Stratigraphic Sequence in Northeastern Kansas: Am. Jour. Sci., vol. 247, pp. 883-889).

1950 - Condra, G. E., and Reed, E. C., recognized one till of Illinoian age in northeastern Nebraska. They classified it as Illinoian because "... of its occurrence above the Pearlette Volcanic Ash bed of the Sappa Formation (Late Kansan) and because it exhibited 'weathering characteristics' intermediate between those of the Kansan and Wisconsinan Tills". (Correlation of the Pleistocene Deposits of Nebraska: Nebraska Geol. Survey Bull. 15A).

1955 - Flint, R. F., mapped Illinoian till on the north side of the Missouri River in South Dakota. He states:

> "The strongest direct stratigraphic implication of the presence of Illinoian Till is in an exposure in Minnehaha County in which a till antedates Loveland Loess and post-dated nonglacial sediments similar to though not proved to be the Sappa Formation of Nebraska geologists.
>
> Further, the presence in Moody County of an exposure of a pre-Loveland till underlain successively by nonglacial allûvium and by a still older till suggests that the till first mentioned is Illinoian, though an earlier date is admissible. Stronger evidence of the Illinoian glaciation of South Dakota, although still indirect, comes from the widespread presence of the Loveland Loess in Iowa and Nebraska, and at several localities in South Dakota. These facts imply extensive glaciation in this region during the Illinoian Stage. Hence the loess and probable age of the till near Chamberlain and in Moody County stand in mutual support.
>
> If the probability of the presence of Illinoian drift in South Dakota is admitted, then it is probable that much of the pre-Wisconsin till exposed in South Dakota is Illinoian, simply because the likelihood of survival is greater for this till than for the two older tills. But the Nebraska geologists are of the opinion that Illinoian drift is not present in Nebraska because of the stratigraphic relations in northeastern Nebraska." (Pliestocene Geology of Eastern South Dakota, U.S.G.S. Prof. Paper 262, p. 30).

Note that contrary to Flint's statement above, Nebraska geologists did recognize Illinoian till in northeastern Nebraska (see Condra and Reed, 1950).

1965 - Reed, E. C., and Dreeszen, V. H., proposed a revision of the Pleistocene classification in Nebraska. In this classification they have proposed two substages for the Nebraskan, three substages for each of the Kansan, Illinoian and Wisconsin. In this classification they

abandoned use of all names implying time-stratigraphy. Local names were applied to the tills previously known as the Nebraskan, Kansan and Illinoian since "... each of these glacial stages is represented by more than one advance and 'retreat' of the ice." (Revision of the Classification of the Pleistocene Deposits of Nebraska: Nebr. Geol. Sur. Bull. 23).

In their classification each of the four stages includes both the glacial and interglacial time. The recognition of a more complex glacial history than outlined earlier was due to data obtained from hundreds of drill holes made specifically for stratigraphic information. Their classification is outlined below.

They recognize two tills of Nebraskan age, the Elk Creek Till of Early Nebraskan age exposed in the vicinity of the village of Elk Creek, Nebraska, and the Iowa Point Till of Late Nebraskan age. The status of this latter till is not clear. Reed and Dreeszen state that "Till of late Nebraskan age has been Penetrated in test drilling at a number of locations in southeastern Nebraska occurring below the Afton soil and resting upon the Seward Formation.... However, a stratigraphically documented outcrop of this till in Nebraska has not been located to date. Therefore, we are designating a locality in northeastern Kansas, reported by Frye and Leonard (1949, p. 887) and classified as 'Nebraska Till', as the type locality of the Late Nebraskan Till and are herewith applying the rock-stratigraphic name of Iowa Point to this deposit."

Frye and Leonard (1949) described two tills separated by a soil at a locality in Doniphan County, northeastern Kansas. The lower till they interpreted as being Nebraskan in age and the upper one Kansan with Afton Soil separating them. However, it should be noted that Frye and Leonard's interpretations were made before it was recognized that two till deposits, each having a well-developed interstadial soil, exists (?) in the Kansan Stage. At the time of Frye and Leonard's investigation whenever two tills were seen in superposition in the area beyond the limits of the Illinoian tills, the lower one was automatically termed Nebraskan Till and the upper one Kansan Till. Why, knowing this and recognizing the possibility of both a multiple Nebraskan Stage and Kansan Stage, Reed and Dreeszen picked this lower till of Frye and Leonard's to be the type Iowa Point Till is not clear. The two tills described by Frye and Leonard could represent Reed and Dreeszen's two Kansan tills, or two Nebraskan tills, or a combination of both a Nebraskan and Kansan till.

When asked for their opinion on the status of the Iowa Point Till, both authors expressed that they were very uncertain of its validity and the senior author stated that "the presence of the Iowa Point Till was very speculative". (Reed, E. C. and Dreeszen, V. H., personal communication, summer 1970).

1968 - The Kansas Geological Survey adopts Reed's and Dreeszen's classification in part. However, they retain stage status for the Aftonian, Yarmouthian, and Sangamonian. (Zeller, Doris E., editor; The Stratigraphic Succession in Kansas, State Geological Survey of Kansas Bulletin 189, 1968).

APPENDIX C

A BRIEF HISTORY OF THE STUDY OF THE "PEARLETTE" VOLCANIC ASH

1880 - Aughey, S., first described the deposits of white silt (volcanic ash) as "flour-like" and named it geyserite because he thought it originated from ancient geysers. (American Mineralogist, vol. 1, no. 5, p. 277-280.)

1885 - Merrill, G. P., noted that the deposits of white silt (volcanic ash) consisted of fragments of pumiceous glass. He recognized the deposits as being volcanic dust and sand of andesitic composition. (Volcanic Dust from Southwestern Nebraska: Science, vol. 5, no. 116.)

1886 - Todd, J. E., proposed that the volcanic activity which produced the volcanic ash was contemporaneous with glaciation in the Dakota and Iowa regions and that deposition occurred in quiet lake waters. (Quaternary volcanic deposits in Nebraska: Science, vol. 7, no. 168.)

1894 - Barbour, E. H., proposed that the source of the ash was to the southwest of the states of Nebraska, Kansas, and Oklahoma. (Abstract, Nebraska Acad. Sci. Proceedings, no. 5, vol. 5, p. 12-17.)

1896 - Cragin, F. W., named the ash Pearlette for the type locality near the old post office at Pearlette, Meade Co., Kansas. He suggested a late Pliocene age for the ash. (Preliminary notice of three Late Neocene terraces of Kansas: Colorado College Studies, vol. 6, p. 53-54.)

1897 - Haworth, E., in reference to the various ash deposits being collectively termed Pearlette stated - "There is no evidence of any relation between the different isolated deposits excepting as it seems probable to some that they must have been formed at about the same time on account of their probable origin as implied by the name volcanic ash. As it is yet an open question regarding the true nature of the material, and much more so regarding its mode of deposition, it is hardly desirable to draw many conclusions from their supposed origin. It is correspondingly less desirable to group the little isolated patches together and assign them to a geologic terrane including nothing else." Apparently at this time Haworth considered the Pearlette ash to be Pliocene in age. (Physical Properties of the Tertiary: Kansas Geol. Bull., vol. 2, p. 247-281.)

1916 - Barbour, E. H., described the ash in some detail. He discussed the properties, origin, and uses of the

Pearlette and Tertiary ashes. (Nebraska Pumicite: Nebr. Geol. Survey Ser. 1, vol. 4, pt. 27.)

1924 - Kay, G. F., interprets the volcanic ash as being interstratified with the Loveland formation in the type area of the latter (Loveland, Iowa). He states:
"Northeast of the village of Little Sioux, in Harrison County, there are along the east slope of the Little Sioux River tills, gravels and related materials which were described by Shimek as the county-line exposures. Here are fine, whitish 'silts' which were thought by Shimek to be part of the section of sand and gravels which he interpreted as being Aftonian in age. Recently these 'silts' were studied by Dr. Alden, who proved that they are volcanic ash. The writer is convinced that this volcanic ash is not of Aftonian age, but is of the same age as the Loveland loess, with which in some of the county-line exposures it is interstratified." (Recent Studies of the Pleistocene in Western Iowa: Abstract, Geol. Soc. America Bull., vol. 35, pp. 71-73.)

1935 - Lugn, A. L., interpreted the ash as being Loveland in age and states "The volcanic ash in the Loveland formation seems to have been deposited in small ponds or lakes, or perhaps along early Loveland valleys." (The Pleistocene geology of Nebraska: Nebr. Geol. Survey Bull. no. 10, 2nd ser., 223 pp.)

1940 - Smith, H. T. U., stated "The individual (ash) deposits represent small, completely isolated bodies and do not constitute any definite stratigraphic unit to which a formation name seems applicable." He believed the ash deposits in Meade and Clark Counties, Kansas, may differ considerably in age. He reported that some deposits were tilted, and that some more indurated than others. He thought that some of the ash deposits might be Tertiary in age. (Geologic Studies in southwestern Kansas: Kansas Geol. Survey Bull. 34, 212 p.)

1943 - Kay, G. F., and Graham, J. B., interpreted the volcanic ash as being Loveland in age; they state:
"The ash is in the lower part of a loess phase of the Loveland formation, or may be associated with Loveland silts and clays showing deposition in water, but changing gradually into the typical eolian loess phase of the overlying Loveland. Frequently, sections of the Loveland which include the volcanic ash indicate that the pumicite was deposited in shallow ponds, lakes or bayous after the sands and gravels of the Loveland age had been deposited. In Iowa, this history is indicated by numerous exposures along Sioux River north of the town of

Little Sioux, Little Sioux Township, Harrison County." (The Illinoian and Post Illinoian Pleistocene Geology of Iowa: Iowa Geological Survey Report 1943.)

1946 - Swineford, A., and Frye, J. C., after a rather intensive study of the Pearlette Ash, concluded: "Volcanic ash occurs in the Great Plains of Kansas and adjacent states at several stratigraphic positions within the Pliocene and Pleistocene deposits. Although at least two different horizons of ash, which may represent three ash falls, are known from the Pliocene, and one or more, possibly representing as many as three ash falls, may occur within the Pleistocene, they can be placed in two natural groups--one of about mid-Pliocene age and the other of about mid-Pleistocene age. (Petrographic comparison of Pliocene and Pleistocene volcanic ash from Western Kansas: Kansas Geol. Surv. Bull. 64.)

1947 - Condra, G. E., Reed, E. C., and Gordon, E. D., state: "However, we found that the Crete-Loveland cycle of erosion and valley-filling started after the ash was deposited. This unconformable relationship between the volcanic ash and the Crete and Loveland formations is now well shown at the Little Sioux locality in Iowa." Hence, they favored a late Kansan or Yarmouth age for the ash rather than a Loveland or early Illinoian age which the Iowa geologists proposed. They thought the ash came from the west and was deposited in lakes and lagoons. (Correlation of the Pleistocene Deposits of Nebraska: Nebr. Geol. Survey Bull. 15, 1947, p. 23.)

1948 - Frye, J. C., Swineford, A., and Leonard, A. B., reported that the ash was rhyolitic in composition. They concluded that the ash was Early Yarmouthian in age on the basis of the molluscan fauna associated with the ash. (Correlation of Pleistocene Deposits of the Central Great Plains with the Glacial Section: Jour. of Geol., vol. 56, no. 6).

1949 - Swineford, A., suggests that the source of the Pearlette is the southwest of Nebraska, Kansas, and Oklahoma. She suggests that the Valley Grande volcanic area of north-central New Mexico was the source. (Source Area of Great Plains Pleistocene volcanic ash: Jour. Geol., vol. 57, p. 307-311).

1957 - Schultz, B., and Tanner, L., assigned a Yarmouth interglacial age to the ash-bearing Sappa formation of Nebraska (Medial Pleistocene fossil vertebrate localities in Nebraska: University of Nebraska State Museum Bull., vol. 4, no. 4).

1958 - Powers, H. A., Young, E. J., and Barrett, P. R., discuss the possible extension of the Pearlette ash into Idaho, Nevada, and Utah. (Possible extension into Idaho, Nevada, and Utah of the Pearlette ash of Meade County, Kansas: (Abst.), Geol. Soc. America Bull., vol. 69, no. 12, pt. 2).

1960 - Young, E. J., and Powers, H. A., suggest that four separate ash falls constitute the Pearlette. (Chevkinite in volcanic ash: Am. Mineralogist, v. 45, p. 875-881.)

1963 - Swineford, A., does not concur with Young's and Power's interpretation on the basis that if more than one ash fall constitutes the Pearlette, there would be observable differences in the glass. Such differences, she indicates, have not been observed. She proposes that for stratigraphic purposes the Pearlette can be considered one ash fall. (The Pearlette Ash as a stratigraphic marker: Kansas Acad. Sci. Trans., vol. 66, no. 3, p. 359-362.)

1964 - Miller, R. D., placed the age of the Pearlette as from Late Kansan to Early Yarmouthian. (Geology of the Omaha-Council Bluffs Area, Nebraska-Iowa: U.S.G.S. Prof. Paper 472, 70 p.)

- Miller, R. D., Van Horn, R., Dobrovolny, E., and Buck, L. P., suggest that the Pearlette consists of four separate ash falls. This is in agreement with Young's and Power's interpretations of 1960. (Geology of Franklin, Webster, and Nuckolls Counties, Nebraska: U.S.G.S. Bull. 1165).

1965 - Wilcox, R., proposes that the source area of the Pearlette ash in Idaho, Utah, and Nevada is in California or Oregon. (Volcanic-ash chronology: p. 807-816 in The Quaternary of the United States, Wright, H. E., Jr., and Frye, D. G., editors: Princeton University Press.)

- Reed, E. C., and Dreeszen, V. H., place the Pearlette in Nebraska as Late Kansan. However, they recognize the possibility of a pre-Pearlette ash in Nuckolls County, Nebraska. (Revision of the Classification of the Pleistocene Deposits of Nebraska: Nebr. Geol. Survey Bull. 23, p. 6).

1967 - Walker, W. B., studied a score or so ash deposits in Nebraska and made the following conclusions:

"1. An analysis of the grain-size data indicates no geographic trend, and hence, no clear indication of source area.

2. The ash deposits are poorly sorted; the purer ashes commonly show a bimodal grain size distribution, the ashy silts are commonly unimodal.

3. The Pearlette Ash cannot be distinguished from the non-Pearlette ash using mineralogical criteria.

4. Refractive index of the glass shards does not serve to distinguish the compared ashes.

5. Specific gravity of the glass shards, is quite variable.

6. Shard shape analysis may give evidence of two different ashes, but because of the great range of values of shape-class-percentages within one ash unit, this evidence should be substantiated.

7. The chemical investigation was inconclusive. The great similarity between Pearlette and non-Pearlette ash considered would seem to indicate that ash derived from chemically similar sources will exhibit like characteristics (George, 1924)."

(Petrography of the Pearlette Volcanic Ash (Pleistocene) in southeastern Nebraska: unpublished MS thesis, University of Nebraska, 1967, p. 50.)

1967 - While employed by the Nebraska Geological Survey I attempted to resolve the "Pearlette problem" by using K-Ar dating. Three samples were submitted to Isotopes, Inc., for dating. It was thought that these samples might be different in age as suggested by stratigraphic relationships. The results obtained by K-Ar dating are compared to fission-track dates obtained from the same ash deposits in 1972.

	1967	1972
Ash site	K-Ar Age (m.y.)	Fission-track age (m.y.)
Dam site	2.0 ± 1.0	0.64 ± 0.07
David City (Cored ash)	7.8 ± 1.2	1.16 ± 0.20
Coleridge	4.9 ± 1.5	1.22 ± 0.17

1970 - Izett, G. A., Wilcox, R. E., Powers, H. A., and Desborough, G. A., reported that they can discern four Pleistocene ashes: the Bishop (0.7 m.y. K-Ar); the Green Mountain Reservoir ash named for its occurrence at Green Mountain, Colorado; and two Pearlette-like ashes -- the Pearlette-like ash Type-O from its occur-

rence on Onion Creek, Grand County, Utah; and the Pearlette-like ash Type-S from its occurrence at the type locality of the Sappa Formation, Harlan County, Nebraska. Two or more of the four ashes occur in single sections at several of the localities in California, Utah, and Colorado.

They report that the Bishop glasses are distinguishable from the Green Mountain Reservoir glasses on the basis of total Fe and CaO content. The Bishop glass contains approximately 0.2% more Fe than the Green Mountain and about 0.1 to 0.2% less CaO.

	Green Mountain	Bishop
Total Fe	.44 to .48%	.63 to .74%
CaO	.62 to .67%	.36 to .74%

The Pearlette-like Type-O and -S ashes are distinguishable from each other by small differences in the total Fe content.

	Pearlette-like Type-O	Pearlette-like Type-S
Total Fe	1.33 to 1.42%	1.29 to 1.15%

As can be seen, the total Fe content also serves to separate the Green Mountain and Bishop ashes from the Pearlette-like ashes.

They find that the Pearlette-like ashes have strong resemblances to Pleistocene air-fall rhyolitic ash from eruptive centers in Yellowstone Park area of Wyoming and Idaho. They differ from the Jemez Mt. centers in New Mexico (the proposed source for the Pearlette suggested by Ada Swineford). The Bishop Ash source is from the Bishop volcanic area of northern California and Oregon. The Green Mountain ash represents later ejecta from the Bishop magma.

The Bishop material has been dated as about 0.7 m.y. The Green Mountain ash is younger than the Bishop. The Pearlette-like Type-O ash is considered less than 0.7 m.y. on the basis of its relationship with the Bishop. The Pearlette-like Type-S is considered significantly older than 0.7 m.y. (The Bishop Ash Bed, a Pleistocene Marker Bed in the Western United States: Quaternary Research, vol. 1, p. 122-132); also, (Wilcox, R. E., Izette, Glen A., and Powers, H. A.: The Yellowstone Park Region as a Source of the Pearlette-like Ash beds of the Great Plains: Am. Quat. Assoc., Abstr. of 1st meeting, Bozeman, Montana, 1970, p. 151.)

1971 - Izett, G. A., Wilcox, D. E., Obradovich, J. D., and Reymolds, R. L., cite evidence for two Pearlette-like ash beds in Nebraska and adjoining areas. Here they assign the Type-S designation to the ashes at the Type locality of the Sappa Formation, the Coleridge ash site and the Butler ash site (cored). The Type-O designation is assigned to the ashes of the Hartford, South Dakota, site and to the County Line Ash Site, Iowa.

The two Pearlette-like ashes correlate chemically with tephra from two of three calderaforming eruptions of the Yellowstone National Park. The Type-S correlates with tephra from the initial explosive phase of the middle ash-flow sheet dated at 1.2 m.y. (K-Ar sanidine). The Type-O ash correlates with tephra from the initial explosive phase of the upper ash-flow sheet dated at 0.6 m.y. (K-Ar sanidine). Also, preliminary measurements of a few ash samples indicate that the Type-O ash has normal and Type-S reverse depositional remnant magnetisms.

(Evidence for two Pearlette-like ash beds in Nebraska and adjoining areas: Geol. Soc. America, Abstracts with Programs, vol. 3, no. 7.)

1972 - Borchardt, G. A., Aruscavage, P. J., and Millard, H. T., Jr., approached the "Pearlette" problem using trace element analysis. They found that three Pleistocene ash beds are discernible on the basis of manganese and samarium concentrations. These ashes were termed the Bishop, the Green Mountain reservoir, and the Pearlette-like. (Correlation of the Bishop Ash, a Pleistocene Marker Bed, using Instrumental Neutron Activation Analysis: Jour. Sed. Pet., vol. 42, no. 2, p. 301-306.)

(Borchardt, G. A., Aruscavage, P. J., and Millard, H. T., Jr., 1972.)

APPENDIX D

Statistical tests concerning the distribution and migration of uranium in volcanic ash from the Dam 7 Ash Site, Seward County, Nebraska.

(A) Density of Spontaneous Fission-tracks in Volcanic Ash from the Dam 7 Ash Site, Seward County, Nebraska

		DATA			
Irradiation level	Replicate Measurements	Etching Time (Sec) 110	120	130	
1	a	21	39	38	
	b	30	24	32	
	c	23	37	36	
	Subtotal	74	100	106	
2	a	24	29	39	
	b	32	43	31	
	c	33	36	38	
	Subtotal	89	108	108	
3	a	33	26	39	
	b	31	41	42	
	c	33	26	35	
	Subtotal	97	93	116	
	Total	260	301	330	891 (Grand Total)

Observations are number of spontaneous fission-tracks per one hundred unit areas (each 150 microns in diameter). The ash was etched in constantly agitated 24% hydrofluoric acid at 23° C.

Analysis of Variance

Source	Degrees of Freedom (d.f.)	Sum of Squares	Mean Square	Variance Ratio	F.05 (critical)
Between etch times (treatment)	2	274.9	137.45	5.56 (2&4 d.f.)	6.94
Between irradiation levels (block)	2	48.2	24.10	0.78 (2&18 d.f.)	3.55
Between etch times within irradiation levels (interaction)	4	98.9	24.73	0.80 (4&18 d.f.)	2.93
Between measurements within irradiation levels within etch time (error)	18	558.0	31.00		
TOTAL	26	980.0			

Tests of Hypotheses

1. Null hypothesis: Interaction variance = 0.
   That is, the variance of the three spontaneous track counts is the same within each subsample--treatment combination. Therefore, the variance due to the interaction term is effectively zero.

   The null hypothesis is accepted because the calculated variance ratio of 0.80 $\overline{c}$ 4&18 d.f. is smaller than the critical value of 2.93 $\overline{c}$ 4&18 d.f.

2. Null hypothesis: Block variance = error variance.
   Since interaction variance is effectively zero, I can test the null hypothesis that the variance of the spontaneous track count is the same between subsamples (blocks) as within subsamples (error).

   The null hypothesis is accepted because the calculated variance ratio of 0.78 $\overline{c}$ 2&18 d.f. is smaller than the critical value of 3.55 $\overline{c}$ 2&18 d.f.

3. Null hypothesis: the mean value of spontaneous tracks/100 areas is the same for each of the three etch periods.

   The null hypothesis is accepted because the calculated variance ratio of 5.56 $\overline{c}$ 2&4 d.f. is smaller than the critical value of 6.94 $\overline{c}$ 2&4 d.f. Therefore, I conclude the number of spontaneous fission-tracks /100 areas obtained by the three etch periods is the same. Thus, the etch period is not critical within these limits.

The three etch periods revealed fission tracks at three successively deeper levels within the ash shards - about 11, 12, and 13 microns deep. Because the density of spontaneous tracks is not significantly different for the three etch periods (and levels in the shards) I conclude that the past distribution of uranium as exhibited by the distribution of

spontaneous fission-tracks was homogeneous and that migration of uranium has not occurred.

Analysis of Variance

Source	Degrees of Freedom (d.f.)	Sum of Squares	Mean Square	Variance Ratio	F.05 (critical)
Between etch times (treatment)	2	1195	597.50	4.07 (2&4 d.f.)	6.94
Between irradiation levels (block)	2	1319	659.50	5.63*(2&27 d.f.)	3.35
Between etch times within irradiation levels (interaction)	4	587	146.75	1.25 (4&27 d.f.)	2.73
Between measurements within irradiation levels within etch times (error)	27	3160	117.04		
TOTAL	35	6261			

B. Density of Spontaneous Plus Induced Fission-tracks in Volcanic Ash from the Dam 7 Ash Site, Seward County, Nebraska

		DATA			
Irradiation level	Replicate Measurements	Etching Time (Sec) 110	120	130	
1	1	131	125	129	
	2	91	114	129	
	3	105	119	114	
	4	115	103	117	
	Subtotal	442	461	489	
2	1	115	144	142	
	2	120	133	134	
	3	103	125	134	
	4	130	122	141	
	Subtotal	468	524	551	
3	1	146	123	146	
	2	122	104	131	
	3	116	123	139	
	4	141	128	130	
	Subtotal	525	478	546	
	Total	1435	1463	1586	4484 (Grand Total)

Observations are number of spontaneous plus induced fission-track per 25-unit areas (each 150 microns in diameter). The ash was etched in constantly agitated 24% hydrofluoric acid at 23° C.

Tests of Hypotheses

1. Null hypothesis: Interaction variance = 0.
   That is, the variance of the four spontaneous plus induced track counts is the same within each subsample-treatment combination and therefore, the variance due to the interaction term is effectively zero.

The null hypothesis is accepted because the calculated variance ratio of 1.25 $\overline{c}$ 4&27 d.f. is smaller than the critical value of 2.73 $\overline{c}$ 4&27 d.f.

2. Null hypothesis: Block variance = error variance.
   Since interaction variance is effectively zero, I can test the hypothesis that the variance of the spontaneous plus induced track counts is the same between subsamples (blocks) as within subsamples (error).

The null hypothesis is rejected because the calculated variance ratio of 5.63 $\overline{c}$ 2&27 d.f. is larger than the critical value of 3.35 $\overline{c}$ 2&27 d.f. Thus, I conclude that the subsample (block) variance is larger than the error variance. This is not surprising since the subsamples received different neutron doses.

3. Null hypothesis: The population mean values of spontaneous plus induced tracks/25 areas is the same for each of the three etch periods.

The null hypothesis is accepted because the calculated variance ratio of 4.07 $\overline{c}$ 2&4 d.f. is smaller than the critical value of 6.94 $\overline{c}$ 2&4 d.f.

The three etch periods revealed fission-tracks at three successively deeper levels within the ash shards about 11, 12, and 13 microns deep. Because the density of spontaneous plus induced tracks is not significantly different for the three etch periods (and levels in the shards) and because the

density of spontaneous tracks appears to be uniform (see analysis of variance of spontaneous tracks), I conclude that the present uranium distribution is homogeneous and that migration of uranium has not occurred.

APPENDIX E

Statistical Analyses of Fission-Track Dates of Volcanic Ashes

A. Statistical Analysis of Fission-track Ages of Chemically Similar Younger Ashes

DATA

Irradiation level	Ash Site					
	Cudahy	Elk Creek	Guthrie	Dam 7	County Line	Hartford
1	0.562	0.598	0.615	0.639	0.745	0.817
2	0.697	0.570	0.631	0.689	0.718	0.790
3	0.654	0.552	0.533	0.600	0.680	0.675
Total	1.913	1.720	1.779	1.928	2.143	2.282

Observations are fission-track ages given in millions of years before present. Each observation is a mean value of one or more determinations per irradiation level. See Table 1-1 and Figure 1-1 for specific locations and terminology.

Analysis of Variance

Source	Degrees of Freedom (d.f.)	Sum of Squares	Mean Square	Variance ratio	F.05 critical	L.S.D.
Between sites (treatment)	5	0.07693	0.01539	5.04* (5&10 d.f.)	4.24	0.100
Between irradiation levels (block)	2	0.01414	0.00707	2.32 (2&10 d.f.)	5.46	
Error	10	0.03046	0.00305			
Total	17	0.12153				

1. Null Hypothesis: the population means of the six groups of fission-track ages are equal.

The null hypothesis is rejected because the calculated variance ratio exceeds the critical value. Thus, I conclude that a significant difference in the mean fission-track age exists between sites. If in fact the null hypothesis is true, I would expect to draw a sample leading to the above conclusions less than 5 per cent of the time.

2. Null hypothesis: the population mean of the fission-track ages obtained by the three levels of irradiation are equal.

The null hypothesis is accepted because the calculated variance ratio is smaller than the critical value.

Results of analysis of variance test indicated that the fission-track ages of the six ash sites represented more than one age population. In order to determine how many populations and which ash sites represented each population, further statistical testing was performed. The method chosen to carry out such hindsight analyses was Duncan's Multiple Range Test.

Duncan's Multiple Range Test

Ash Site					
(A)	(B)	(C)	(D)	(E)	(F)
Elk Creek	Guthrie	Cudahy	Dam 7	County Line	Hartford
0.573	0.593	0.638	0.643	0.714	0.761

Observations are the mean fission-track age for each ash site. The underlines indicate grouping of means whose differences are insignificant at alpha of 0.05.

Results of the analyses using Duncan's multiple range test indicate that two populations of fission-track ages are represented by the six sites. One group is that represented by cluster ABCD (mean age 0.61 $\pm$ 0.04 m.y.) and the other by cluster EF (mean age 0.74 $\pm$ 0.04 m.y.). However, the age of the ash at the County Line Section seems to overlap both groups. In order to resolve the problem of whether the age of the ash at the County Line Section is more similar to that of group ABCD or to that of F, the ash dates were subjected to further statistical testing as shown below.

Paired-t Test No. 1

Irradiation Level	Ash Site Cluster ABCD	E
1	0.604	0.745
2	0.647	0.718
3	0.585	0.680

t calculated = -4.98^{*} $\bar{c}$ 2 d.f.

$t_{.05}$ critical = $\pm$ 4.303 $\bar{c}$ 2 d.f.

Observations are fission-track ages in millions of years before present and are averaged for each irradiation level. Cluster of ash site ages based on Duncan's Multiple Range Test.

Null hypothesis: the population means of the fission-track ages obtained for sites ABCD is the same as that obtained for site E.

I reject the null hypothesis because the calculated t-value exceeds the absolute value of the critical value. I therefore conclude that the mean age of the ash at site E (County Line) is significantly different than the mean age of the ash at sites ABCD.

Paired-t Test No. 2		
Irradiation Level	Ash Site County Line (E)	Hartford (F)
1	0.745	0.817
2	0.718	0.790
3	0.680	0.675
t calculated = -1.80 $\bar{c}$ 2 d.f.		
$t_{.05}$ critical = $\pm$ 4.303 $\bar{c}$ 2 d.f.		

Observations are fission-track ages in millions of years before present.

Null hypothesis: the population means of the fission-track ages obtained for site E is the same as those obtained for F.

I accept the null hypothesis because the calculated t-value does not exceed the absolute value of the critical value. I conclude that the age of the ash at site E (County Line) is the same as that at site F (Hartford).

Summary

Based on analysis of variance, Duncan's multiple range tests and paired-t tests I conclude that the ashes at sites ABCDEF fall into two populations. One population is represented by the ash at the Hartford Ash Site and the County Line Ash Site and has a mean age of about 0.74 $\pm$ 0.04 m.y. The other population is represented by the ashes at the Cudahy Ash Mine, Elk Creek Ash Site, Dam 7 Ash Site, and Guthrie Ash Site and has a mean age of about 0.61 $\pm$ 0.04 m.y.

(B) Statistical Analysis of Fission-Track Ages of Chemically Dissimilar Younger Ashes

Paired-t Test		
Irradiation level	Ash Site	
	Hartford	Nuckolls
1	0.781	0.792
2	0.754	0.996
3	0.678	0.670
t calculated = -1.02		
$t_{.05}$ critical = $\pm$4.303		

Observations on fission-track ages in millions of years before present. Each observation is a mean value of one or more determinations per irradiation level.

Null hypothesis: the population means of the fission-track ages of the ash at Hartford, South Dakota, is equal to those of the ash in Nuckolls County, Nebraska.

I accept the null hypothesis because the calculated t-value does not exceed the absolute value of the critical value.

(C) Statistical Analysis of Fission-track Ages of Chemically Similar Older Ashes

Data			
Irradiation level	Ash Site		
	Sappa	David City	Coleridge
1	1.630	1.089	1.086
2	1.298	1.381	1.405
3	0.837	1.008	1.166
Total	3.765	3.478	3.657

Observations are fission-track ages in millions of years before present. Each observation is a mean value of one or more determinations per irradiation level.

Analysis of Variance

Source	Degrees of Freedom (d.f.)	Sum of Squares	Mean Square	Variance Ratio	F.05 (tabular)
Between sites (treatment)	2	0.01401	0.00701	0.12	6.94
Between irradiation levels (block)	2	0.20663	0.10332	1.70	6.94
Error	4	0.24265	0.06066		
Total	8	0.46329			

Null hypothesis: The population means of the fission-track ages of each of the three ash sites are equal.

I accept the null hypothesis because the calculated variance ratio does not exceed the critical value.

APPENDIX F

Measured Sections

City Wide Rock Quarry - Section 1

Location: NE 1/4 NW 1/4 sec. 29, T. 13 N., R. 13 E., Sarpy County, Nebraska.

Unit		Approximate Thickness (feet)
1.	Silt, slightly clayey and sandy, very fine to fine sand, friable, porous, noncalcareous, light yellowish-brown (Peoria Loess)----------	2
2.	Silt, as above but medium reddish-brown and contains carbonaceous specks, (Loveland Loess)----------	14
3.	Upper till, silt-clay, moderately sandy, slightly gravelly, upper 3 feet is grayish brown, has a noncalcareous matrix and contains secondary carbonate concretions. Below 3 feet till matrix becomes moderately calcareous, light to medium gray, and dontains small secondary carbonate concretions and blocks of interbedded sand and silt----------	16
4.	Middle till, silt-clay, moderately sandy, slightly gravelly, yellowish-brown with some light gray mottling, moderately calcareous, contains scattered silt-sand blocks, contains abundant secondary carbonate concertions in upper 5 feet. Basal two feet of this till is light gray in color.----------	24
5.	Silt, moderately clayey, slightly sandy, very fine to medium sand, noncalcareous, dark grayish-brown to reddish-brown, contains minute iron/manganese nodules ("soil")----------	4
6.	Lower till, silt, moderately clayey and sandy, slightly gravelly, slightly to moderately calcareous matrix, pale-yellow with some gray mottling, contains lime-filled cracks in upper few feet. A discontinuous "zone" of secondary carbonate concretions occurs about eleven feet below the top of this till.This till rests on a striated and grooved surface. The striations and grooves strike N 25° E.----------	19

City Wide Rock Quarry - Section 2

Location: NW 1/4 NE 1/4 sec. 29, T. 13 N., R. 13 E.
Sarpy County, Nebraska.

Unit		Approximate Thickness (feet)
1.	Silt, slightly clayey and sandy, very fine to fine sand, porous, friable, light yellowish-brown, noncalcareous (Peoria Loess)----------	7
2.	Silt, as above but light reddish-brown, (Loveland Loess)----------	18
3.	Upper till, silt, very clayey, moderately sandy, slightly gravelly, contains some secondary carbonate nodules, light brownish-gray, noncalcareous matrix----------	10
4.	Middle till, silt, very clayey, moderately sandy, slightly gravelly, upper 6 feet very slightly calcareous matrix, yellowish-brown with olive-brown mottling. This grades into moderately to very calcareous till with a light brownish-gray color and some olive-gray mottling. Contains some secondary carbonate grains. The basal 2 feet contains numerour cobbles and boulders of local limestone and is pinkish-brown in color. It appears that this color is due to incorporation of underlying reddish clay silt which is associated with a paleosol----------	16
5.	Lower till "A", silt, very sandy, moderately clayey, slightly gravelly, contains secondary carbonate nodules in upper 6 feet, contains occasional blocks of silt, yellowish-brown, moderately calcareous matrix----------	12
6.	Sand and silt, slightly clayey, very fine to fine sand, yellowish-brown, very slightly calcareous. These silts appear to have been channeled into the underlying till and then planed off by the ice that deposited the overlying till. There does not appear to be a weathering horizon on this unit-------	8

Unit		Approximate Thickness (feet)
7.	Lower till "B", silt, very sandy, moderately clayey, slightly gravelly, contains some secondary carbonate nodules, light yellowish-brown to light brownish-gray, slightly to moderately calcareous matrix. This unit rests on a grooved and striated bedrock surface. (Winterset limestone of Pennsylvanian Age) The glacial grooves and striations strike N 25° E.--------	16

Type Locality of Elk Creek Till

Location: NW 1/4 SW 1/4 sec. 1, T. 3 N., R. 11 E., Pawnee County, Nebraska. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Sand, brown-gray, medium-grained, occurs in channels cut into underlying silts	10
b.	Silt and clay, medium to light gray, contains calcareous concretions, lower part grades to very fine gray sand--	66
c.	Till (Elk Creek), boulder clay, medium to brownish, calcareous, rich in limestone and shale pebbles, contains some secondary carbonate concretions	5 to 15

Elk Creek Ash Site

Location: SW corner SW 1/4 SE 1/4, sec. 26, T. 4 N., R. 11 E., Johnson County, Nebraska, Nebraska Geological Survey Test Holes AH-6-70 and AH-14-70

Unit		Approximate Thickness (feet)
a.	Silt, moderately clayey, slightly sandy, very fine to fine sand, brown, non-calcareous	2
b.	Silt, moderately sandy and clayey, very fine to medium sand, contains trace of pebbles, medium red-brown, noncalcareous	7
c.	Volcanic ash; slightly silty and clayey, pinkish white	1
d.	Silt; moderately clayey, slightly sandy, very fine sand, upper 3 feet greenish gray, lower 5 feet light brown, non-calcareous throughout	8
e.	Clay; moderately silty, contains carbon specks and iron-manganese pellets, dark brown, noncalcareous	0.5
f.	Sand; moderately silty, slightly clayey and very fine to medium sand, yellowish brown, noncalcareous	5
g.	Sand; slightly silty and clayey, medium to coarse-grained sand, brown, noncalcareous	5
h.	Silt; very sandy, moderately clayey, very fine to very coarse sand, contains some gravel, brown, very slightly calcareous	12
i.	Till; silt, very clayey, moderately sandy, pebbly, brown, moderately calcareous, becomes mottled olive and grayish brown about 12 feet below top and dark gray to black with greenish-gray mottling about 50 feet below top	70
j.	Silt; moderately clayey and sandy, very fine to medium sand, very slightly calcareous	10
k.	Sand and silt; interbedded, contains shale fragments, greenish gray	8
l.	Shale and limestone bedrock	2

Dam 7 Ash Site

Location: NE 1/4 NE 1/4 NW 1/4, sec. 26, T. 9 N., R. 2 E., Seward County, Nebraska, (Nebraska Geological Survey Test Hole AH-5-70)

Unit		Approximate Thickness (feet)
a.	Silt; slightly to moderately clayey, moderately sandy, very fine to fine sand, yellowish-brown, noncalcareous	7
b.	Silt, slightly to moderately clayey, very sandy, very fine to medium sand, reddish-brown, ncncalcareous----------	8
c.	Sand, slightly silty and clayey, contains some gravel, sand coarse to very coarse-grained, very gravelly in basal 1 foot, yellowish-brown to reddish brown, non-calcareous----------	10
d.	Silt; moderately clayey and sandy, very fine to fine sand, light grayish-brown to yellowish brown, noncalcareous---	10
e.	Volcanic ash; slightly to very silty and slightly clayey, light gray to grayish-brown, noncalcareous----------	5
f.	Silt; slightly clayey and sandy, very fine to fine sand, light reddish brown, non-calcareous----------	6
g.	Silt, slightly to moderately clayey, moder-ately sandy, very fine to medium sand, dark reddish-brown, noncalcareous---	8
h.	Sand; moderately silty, slightly clayey, very fine to fine sand, light reddish-brown, noncalcareous----------	5.5 drilled

David City Ash Site

Location: SE corner sec. 32, T. 15 N., R. 3 E., Butler County, Nebraska, (Nebraska Geological Survey Test Holes 16-B-48 and 19-B-66)

Unit		Approximate thickness (feet)
a.	Clay, moderately to very silty, yellowish-brown with some light gray mottling, noncalcareous	5
b.	Silt; (loess) slightly to moderately clayey, slightly sandy, contains secondary carbonate nodule, light brownish-gray to yellowish-brown, noncalcareous----------	21
c.	Clay; very silty, dark reddish-brown noncalcareous----------	6
d.	Silt, moderately clayey, medium reddish brown, noncalcareous----------	28
e.	Silt, moderately to very clayey, sandy, true gravel, light yellowish-brown, noncalcareous	12
f.	Till; silt, moderately to very clayey, slightly sandy, upper 4 feet leached, contains secondary carbonate nodules in next 5 feet, light yellowish-brown, slightly calcareous----	28
g.	Sand, and gravel; upper 6 feet mainly sand, sand and gravel below this, very fine to coarse sand, gravel is small to very coarse, yellowish-brown----------	12
h.	Till, clay, very silty, sandy and gravelly, medium gray, slightly calcareous----	41
i.	Silt; very clayey, slightly sandy, contains some secondary carbonate concretions, light reddish brown, slightly calcareous--	17
j.	Volcanic ash; slightly silty, light gray to white----------	7
k.	Silt; moderately clayey, light brownish-gray to pinkish, moderately to very calcareous, sandy in lower 4 feet----------=	15
l.	Sand and gravel; fine sand to fine gravel, light brownish gray to pink, noncalcareous	4

m.	Silt; slightly clayey and sandy, light brownish-gray, contains some secondary carbonate nodules about 20 feet below top of unit, noncalcareous	56
n.	Sand and gravel; fine sand to fine gravel, light brownish gray, noncalcareous	6
0.	Shale and limestone bedrock	39

Nuckolls County Ash Site

Location: NE 1/4 SE 1/4, sec. 26, T. 3 N., R. 8 W., Nuckolls County, Nebraska. North of dam spillway on small drain.

Unit		Approximate thickness (feet)
a.	Silt; slightly clayey and sandy, very fine to fine sand, grayish to yellowish-brown, noncalcareous----------	3
b.	Silt; slightly to moderately clayey, slightly sandy, contains some volcanic ash shards, noncalcareous----------	2
c.	Volcanic ash; white, massive, compact at base, noncalcareous----------	1
d.	Silt; slightly to moderately clayey, slightly sandy, light gray to reddish gray, noncalcareous----------	2
e.	Silt; moderately clayey, slightly sandy, laminated, light brown, noncalcareous	18

Type Locality of Sappa Formation

Location: NW 1/4, NW 1/4, SE 1/4, sec. 11, T. 2 N., R. 20 W., Harlan County, Nebraska. Description from Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Loess; gray to light brownish-gray------	25
b.	Silt; dark gray, humic, soil-like-------	2
c.	Silty sand, reddish-brown, upper part clayey, becoming sandy downward-------	9
d.	Sand and gravel; sand, fine-grained in upper part, gravelly in lower two and one-half feet----------	4
e.	Silt; light gray to greenish-gray, indurated in upper foot, middle part clayey	6
f.	Silt-sand; light greenish-gray, massive to laminated in upper third, laminated in middle third, massive in lower third----------	5
g.	Sand; gray to light-greenish gray, laminated and bedded in upper 2.2 feet, lower 4 to 6 feet is medium to very large-grained with some gravel in lower part----------	8
h.	Volcanic ash (Sappa Formation); white, massive, with 2 to 4 fnch clayey section 1.7 feet to 3 feet below top, laminated in lower -7 foot----------	6
i.	Silt, (Sappa Formation); very sandy, greenish-gray----------	1
j.	Sand (Sappa Formation); light gray to greenish-gray, fine-grained, laminated to massive----------	13

Type Locality of Nickerson Till

Location: SE 1/4 SW 1/4 sec. 8, T. 18 N., R. 9E., Washington County, Nebraska. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Silt (loess); light brownish-gray-------	6.5
b.	Silt; dark brown-gray, soil-like, humic-	1.5
c.	Silt; reddish-brown, clayey, sandy with a 6 inch zone at base----------	6.0
d.	Till; boulder clay, yellow-brown to brown-gray, oxidized, calcareous------	7.5
e.	Silty clay; dark brown to chocolate colored, secondary lime-enriched, slightly sandy----------	2.8
f.	Till (Nickerson); boulder-clay, medium gray to yellowish, becoming dark gray in lower part; zone of secondary carbonate accumulation in upper foot--	12.0

Type Locality of Cedar Bluffs Till

Location: SW 1/4 NE 1/4 NW 1/4, sec. 24, T. 17 N., R. 7 E., Saunders County, Nebraska. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Silt (loess); light brownish-gray, channeled into underlying units-------	2 to 10
b.	Clayey silt, reddish-brown, part sandy, top eroded, channeled into underlying till----------	2 to 5
c.	Till (Cedar Bluffs); boulder clay moderately silty and sandy, yellow-brown to light brown grading to light gray to light brown-gray. Upper four feet, where uneroded, is lime enriched------	17 to 26
d.	Silty clay; dark gray, humic, leached with rare secondary lime. Remainder of soil profile is in upper part of till unit below----------	1
e.	Till, boulder clay, moderately silty and sandy, upper 8 inches is partially leached and light brown-gray in color, next lower 7 inches is secondarily lime-enriched zone, next lower 4 feet is light brown-gray to yellowish and unleached. Lowest 13 feet exposed is gray calcareous till with some light brown-gray mottling----------	20

Lype Locality of Clarkson Till

Location: SW 1/4 SW 1/4 SE 1/4 sec. 25, T. 22N., R. 2 E., Stanton County, Nebraska. Nebraska Geological Survey Test Hole A22-2-25dcc. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Silt (loess); brownish-gray to olive-brown, slightly clayey, slightly to moderately calcareous except in upper 12 feet which is leached	59.0
b.	Silt; medium gray, noncalcareous in upper 9 feet, becoming darker downward, very dark brownish gray to black and carbonaceous in lower 2 feet. Paleosol at top.----------	11.0
c.	Silt; moderately to very clayey, medium dark brownish-gray, noncalcareous, sandy to gravelly at base, paleosol at top----------	7.0
d.	Till; (Clarkson), boulder clay, silty to sandy and pebbly, yellowish brown to olive gray mottled in upper 37.6 feet, olive gray to brownish in lower 20 feet, moderately calcareous except for upper 26 feet which is noncalcareous, very clayey and brownish in color----------	58.0
e.	Silty-clay; medium reddish-brown, leached except for secondary carbonate concretions----------	8.0
f.	Till; boulder clay, silty to sandy, yellowish-brown in upper 57 feet, lower part medium to dark gray----------	252.0
g.	Sand, medium gray, very fine to medium grained, slightly calcareous----------	9.0
h.	Till; boulder clay, medium dark gray, silty to sandy to pebbly, calcareous--	11.5
i.	Shale (Carlile)----------	22.0

Type Locality of Hartington Till

Location: SW 1/4 sec. 13, T. 31 N., R. 1 E., Cedar County, Nebraska. Nebraska Geological Survey Test Hole A31-1-13ccc. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Silt, brownish-gray grading downward to olive gray, moderately clayey in upper part grading downward to very sandy near base, moderately calcareous in lower ten feet----------	14.8
b.	Sand and gravel; grades from fine sand to medium gravel, common limestone grains----------	2.7
c.	Till (Hartington); boulder clay, yellowish-brown to olive gray in upper part grading to medium dark gray in lower part, silty to sandy and pebbly, moderately calcareous throughout-------	20.8
d.	Silt; light olive gray, upper part is a clayey silt, lower part grades to sandy silt, snail fauna throughout, some concretionary limy zones-------	4.8
e.	Till; boulder clay, silty to sandy to pebbly, moderately calcareous throughout, medium brownish-gray in upper part, medium dark gray in middle and lower part----------	32.3
f.	Silt and clay, medium gray, moderately calcareous, rare snails in upper part	5.7
g.	Sand; very fine to very coarse-grained with some gravel, slightly calcareous throughout----------	42
h.	Silt; yellowish-gray, moderately clayey, moderately calcareous----------	9.8
i.	Sand; very fine to very coarse-grained, some gravel at base----------	15.6
j.	Silt and clay; olive gray, upper part dark brown-gray, moderately calcareous	8

Coleridge Ash Site

Location: NW 1/4 NE 1/4 NE 1/4, sec. 11, T. 29 N., R. 1 E., Cedar County, Nebraska (Nebraska Geological Survey Test Hole AH-11-70

Unit		Approximate thickness (feet)
a.	Till; silt, very clayey, moderately sandy, slightly pebbly, contains secondary carbonate concretions throughout, light yellowish-brown, moderately to very calcareous	9
b.	Silt; slightly clayey, light brown with pinkish tint, noncalcareous	3
c.	Volcanic ash; white, noncalcareous	1.5
d.	Silt; moderately clayey, slightly sandy, very fine sand, noncalcareous upper 3 feet, then slightly to moderately calcareous, contains scattered secondary carbonate concretions, light reddish-brown	28
e.	Sand; slightly silty, very fine to medium sand, yellowish to pinkish brown, noncalcareous	55 drilled

Type Locality of Santee Till

Location: SE 1/4 SE 1/4 NW 1/4 sec. 29, T. 33 N., R. 4 W., Knox County, Nebraska. Description after Reed and Dreeszen, 1965.

Unit		Approximate Thickness (feet)
a.	Silt (loess); light brownish-gray to buff-	5
b.	Till (Santee); clay, slightly sandy to pebbly, medium dark gray, calcareous throughout, top eroded.----------	
c.	Silt; brownish-gray, bedded, upper part clayey, becomes more sandy downward.--	10
d.	Sand; grading down to sand and gravel, poorly exposed----------	10 exposed

Hartford Ash Site

Location: SW 1/4 NE 1/4, sec. 11, T. 102 N., R. 51 W., Minnehaha County, South Dakota. Description after Flint, 1955.

Unit		Approximate thickness (feet)
a.	Loess, light olive-brown to yellowish gray, grading downward into gray with brown mottling, calcareous----------	7
b.	Till; clay-rich matrix, contains numerous stones, crumbly, faintly jointed, olive-brown when moist, yellowish-gray when dry----------	15
c.	Silt, clayey, loesslike, massive, compact, brown to yellowish-brown, upper 2 feet leached----------	17
d.	Volcanic ash, silty with silt content decreasing downward to basal 0.4 foot of pure ash, white, unstratified, noncalcareous----------	2
e.	Silt; clayey, compact, massive, olive-gray at top grading downward to grayish olive, noncalcareous----------	3
f.	Till, silt-clay, pebbly, tough, light olive-gray, upper 3 inches leached, remainder calcareous	5-25
g.	Silt, loesslike, contains occasional pebbles, very tough, brownish-gray, slightly calcareous----------	3-13
h.	Till, silt-clay, tough, jointed, light olive-brown, calcareous, filled-in cray fish humous at top----------	12-18
i.	Pre-Cambrian Sioux Quartzite----------	

Cemetery Section, Harrison County, Iowa

Location: Across from cemetery on east side of N-S county road in NW 1/4, NE 1/4 sec. 5, T. 81 N., R. 44 W., Harrison County, Iowa.

Unit		Approximate Thickness (feet)
a.	Till; silt, very clayey, moderately sandy, slightly pebbly, calcareous ---------	10
b.	Silt; moderately to very sandy, slightly clayey and pebbly, humic, dark grayish-brown, moderately calcareous --------	4
c.	Till; silt, very clayey, moderately sandy, slightly pebbly, calcareous, contains secondary carbonate concretions in upper 2 feet.----------	15 exposed

County Line Section, Iowa

Location: NW 1/4 NE 1/4, sec. 5, T. 81 N., R. 44 W., Harrison County, Iowa

Unit		Approximate thickness (feet)
a.	Topsoil----------	2
b.	Silt; (loess), slightly sandy and clayey, very fine sand, friable, contains rootlet tubules, light yellowish-brown with light gray mottling, noncalcareous---------	2
c.	Silt; (loess), slightly sandy and clayey, very fine to fine sand, friable, contains rootlets tubules, light reddish brown, noncalcareous----------	6
d.	Silt; moderately clayey, slightly sandy, very fine sand, manganese oxide stains, medium yellowish brown, noncalcareous. Contains three thin (about .3 foot thick) dark brown, clayey, humic? layers (paleosols?) that merge laterally to form a single paleosol (?)----------	5
e.	Silt; moderately clayey, slightly sandy, very fine sand, contains carbon specks and secondary carbonate nodules, reddish brown, noncalcareous matrix (paleosol?)	1.3
f.	Silt; slightly clayey and sandy, very fine sand, yellowish brown, calcareous----	0.7
g.	Sand; very fine to very coarse, moderately silty, cross-bedded, contains minor amount of fine gravel----------	0.8
h.	Silt; moderately sandy, slightly clayey, very fine to fine sand, medium yellowish brown, upper 0.8 foot noncalcareous-	2.5
i.	Limestone; discontinuous layer of secondary carbonate concretions, they contain very fine to fine sand and silt, brownish-white	0.2
j.	Silt and sand; alternating layers of sand and silt, individual layers are only 2 to 4 inches thick. Soil is very fine to medium, silty, medium yellowish-brown and slightly calcareous. Silt is moderately sandy, slightly clayey, light yellowish-brown and calcareous----------	2.3

k.	Limestone; discontinuous layers of secondary carbonate concretions, light tan	0.2
l.	Silt; moderately sandy, slightly clayey, laminated, light yellowish-brown, calcareous	0.8
m.	Limestone; discontinuous layers of secondary carbonate concretions, light tan----	0.2
n.	Silt; moderately sandy, slightly clayey, very fine to medium sand, contains few lenses of sand, silts are bedded, yellowish-brown, moderately calcareous----------	3.3
o.	Silt, moderately clayey, slightly sandy, medium yellowish-brown, slightly calcareous	1.3
p.	Silt; moderately, sandy, slightly clayey, contains some volcanic ash shards, pinkish-brown, noncalcareous----------	1.8
q.	Silt, moderately sandy, slightly clayey, contains more ash than unit p, light brown, noncalcareous----------	1.2
r.	Volcanic ash, very silty, slightly clayey, pinkish white, noncalcareous--------	0.8
s.	Volcanic ash; quite pure, grayish white	0.8
t.	Silt; very sandy, slightly clayey, very fine to medium sand, grayish-brown with light gray mottling and iron-manganese stains, friable, noncalcareous----------	1.8
u.	Silt; very clayey, slightly sandy, contains occasional snail shells, mottled light gray and dark brownish gray, noncalcareous	0.2
v.	Silt; moderately sandy, slightly clayey, very fine to fine sand, contains iron oxide stains, light yellowish to grayish-brown, noncalcareous----------	1.8
w.	Silt; moderately to very clayey at top grading to slightly clayey at base, slightly sandy, grayish-brown at top grading to orange-brown at base due to increase in amount of iron oxide stains, noncalcareous	2.5
x.	Sand and gravel; alternating layers of crossbedded sandy gravel and gravelly sand, contains pebbles and cobbles, iron and manganese-oxide stained, reddish-brown to orange-brown, noncalcareous	25 exposed

Guthrie County Ash Site

Location: NE 1/4 SE 1/4, sec. 8, T. 78 N., R. 33 W., Guthrie County, Iowa (Nebraska Geological Survey Test Hole AH-1-72)

Unit		Approximate Thickness (feet)
a.	Silt; moderated, clayey, slightly sandy, very fine to fine sand, yellowish to reddish-brown, noncalcareous. Volcanic ash lens about 1 foot thick crops out in these silts about 150 feet south of drill hole----------	12
b.	Till; silt, moderately clayey, moderately sandy, pebbly, medium brown to yellowish-brown with light gray mottling, slightly to moderately calcareous----------	36
c.	Till, as above but grading from olive in upper 7 feet to dark gray till below	42

Type Area of Kansan and Pre-Kansan Tills near Afton, Union County, Iowa.

Location: On the south slope of Twelve Mile Creek directly south of Afton, Iowa. In the SW 1/4 NW 1/4, sec. 29, T. 72N., R. 29 W., Union County, Iowa. Section measured on east side of highway number 169 opposite station number 617 which is numbered on edge of pavement slab. The presence of Kansan till over Nebraska till was described at or near this locality by George F. Lake and Earl T. Apfel in 1928.

Unit		Approximate Thickness (feet)
a.	Loess; slightly clayey and sandy, yellowish-brown, friable, leached----------	7
b.	Till (Kansan); silt, very clayey, moderately sandy, slightly pebbly, yellowish-brown with some light gray mottling grading to brownish-gray in lower few feet, upper four feet leached, remainder moderately calcareous, contains abundant secondary carbonate concretions 5 to 10 feet below top----------	19
c.	Clay; moderately to very silty, slightly sandy, contains scattered pebbles, medium gray, leached----------	12
d.	Till (Nebraskan); silt, very clayey, moderately sandy, slightly pebbly, grayish-brown, upper 2 feet leached----------	5 exposed

Borchers Ranch Ash Site

Location: NW 1/4 NE 1/4, sec. 21, T. 33 S., R. 28 W., Meade County, Kansas (Type locality of Meade and Crooked Creek Formations). Description copied from Hibbard, 1949, with his permission and modified after Frye, 1942.

Unit		Thickness (feet)
a.	Silt, sand and some clay, tan to buff brown, massive. Contains sand and some caliche. The surface at the top of bluff is covered with a rubble of caliche-	14.8
b.	Silt, sandy, gray to tan----------	5.4
c.	Clay, with some silt and sand, light gray, massive. Breaks with a conchoidal fracture when dry----------	4.5
d.	Silt, clay, and some sand, gray massive, containing a few calcareous nodules (Borchers fauna)----------	6.4
e.	Pearlette Ash member. Volcanic ash, pearl gray, lenticular, somewhat impure---	7.1
f.	Clay, silt, and some sand, tan gray and brown gray, massive. Cudahy fauna occurs in top 12 inches and base of ash----	9.5
g.	Sand, silt and coarse gravel, brown, contains abundant nodules. Grades upward into red-brown to reddish sandy silt---------	8.8
h.	Stump Arroyo member. Sand coarse, reddish to light tan, and well sorted, containing white quartz pebbles, grading upward into finer more poorly sorted sand, calcareous nodules at top	10.1
	Unconformity	
	Ogallala formation	
	Total thickness of Ogallala formation	78.0
	Permian (not exposed, known from test hole)	

References

Reed, E. C., and Dreeszen, V. H., 1965, Revision of the Classification of the Pleistocene Deposits of Nebraska: Nebraska Geol. Survey Bull. 23, 65 p.

Flint, R. F., 1955, Pleistocene Geology of Eastern South Dakota: U.S.G.S. Prof. Paper 262.

Kay, G. F., and Apfel, E. T., 1928, The pre-Illinoian Pleistocene Geology of Iowa: Reports of Iowa Geological Survey, vol. 34.

Hibbard, C. W., 1949, Pleistocene Stratigraphy and Paleontology of Meade County, Kansas: Contrib. Mus. Paleont., Univ. Michigan, vol. 7, no. 4, p. 63-90.

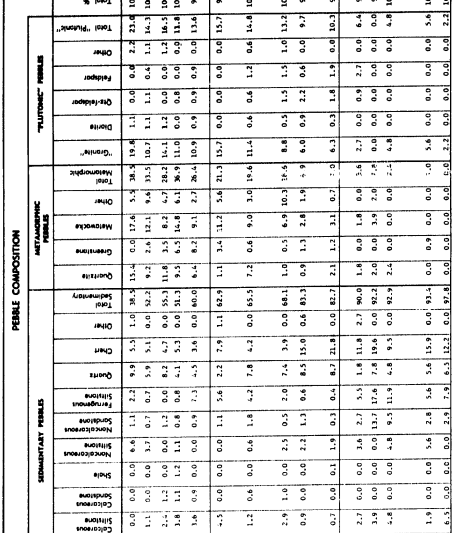
APPENDIX G

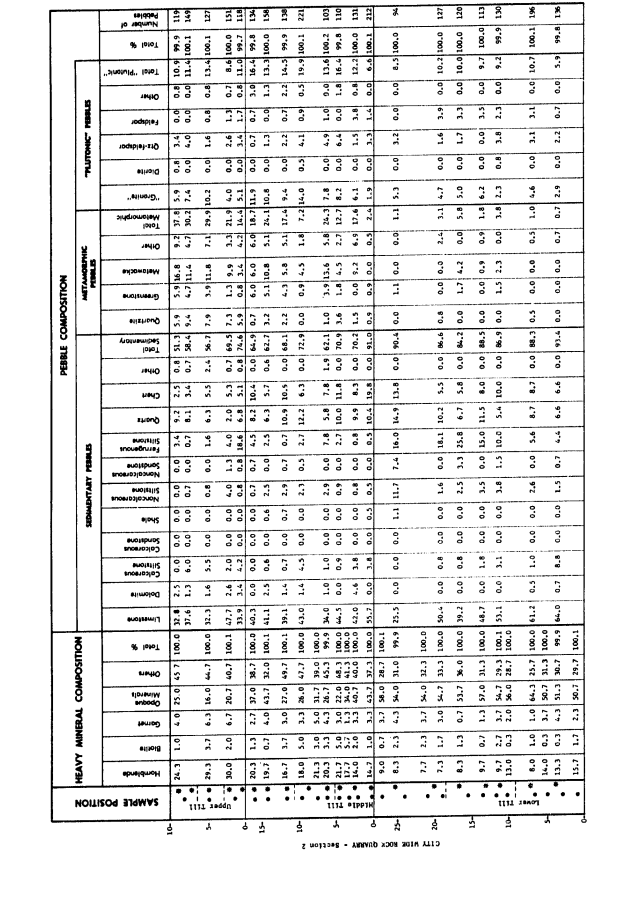
Primary Heavy Mineral and Pebble Count Data for Glacial Tills

• denotes position of heavy mineral samples

* denotes position of pebble samples

--- denotes subdivision of till units into upper, middle, and lower portions.





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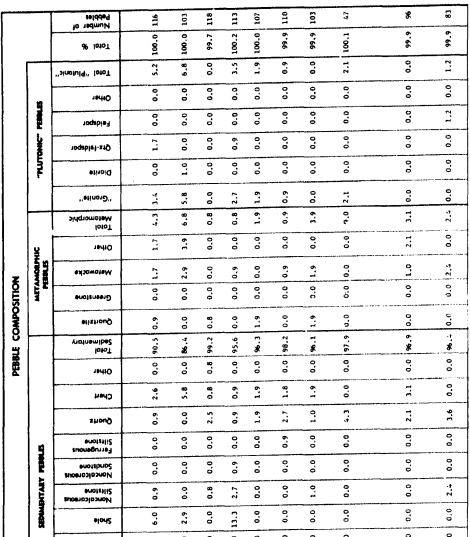
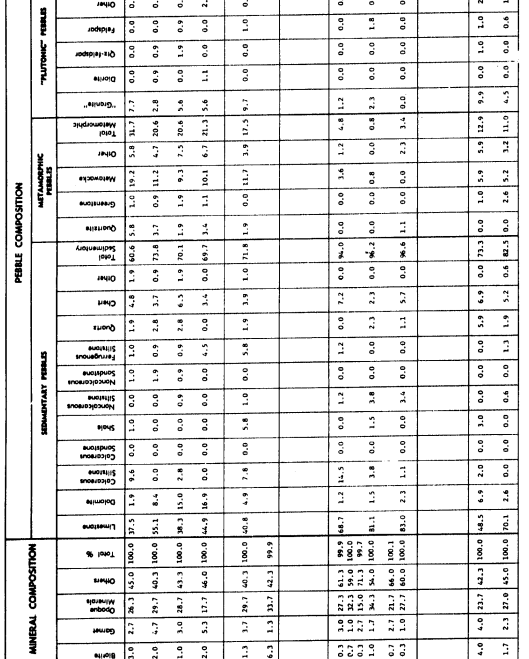


DAVID CITY ARI SITE

SAMPLE POSITION	HEAVY MINERAL COMPOSITION						PEBBLE COMPOSITION																			
							SEDIMENTARY PEBBLES										METAMORPHIC PEBBLES					"PLUTONIC" PEBBLES						
	Hornblende	Biotite	Garnet	Opaque Minerals	Others	Total %	Limestone	Dolomite	Calcareous Siltstone	Calcareous Sandstone	Shale	Noncalcareous Siltstone	Noncalcareous Sandstone	Ferruginous Siltstone	Quartz	Chert	Other	Total Sedimentary	Quartzite	Greenstone	Meta-rhyolite	Other	Total Metamorphic	"Granite"	Diorite	Qtz-feldspar	Feldspar	Other	Total "Plutonic"	Total %	Number of Pebbles
Upper Till	26.7	2.3	4.0	25.3	41.7	100.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	6.7	6.7	0.0	0.0	33.3	6.7	0.0	26.7	20.0	53.3	6.7	0.0	0.0	6.7	0.0	13.3	100.2	15
	28.3	5.3	4.3	22.3	39.7	99.9	29.2	0.0	0.0	0.0	0.0	12.5	0.0	4.2	4.2	0.0	0.0	50.0	0.0	4.2	20.8	8.3	33.3	16.7	0.0	0.0	0.0	0.0	16.7	100.1	24
							45.8	0.0	0.0	0.0	0.0	6.8	0.0	5.1	6.8	3.4	0.0	67.8	0.0	1.7	11.9	0.0	13.6	13.6	0.0	1.7	1.7	1.7	18.6	100.2	59
	31.3	5.7	5.7	19.0	38.3	100.0	33.3	0.0	0.0	0.0	0.0	13.0	0.0	3.7	3.7	0.0	0.0	53.7	1.9	9.3	16.7	3.7	31.5	9.3	0.0	1.9	0.0	3.7	14.8	100.2	54
	25.3	2.0	2.3	30.7	39.7	100.0	43.2	0.0	0.0	0.0	0.0	2.7	0.0	2.7	2.7	2.7	0.0	56.1	0.0	8.1	13.5	2.7	24.3	21.6	0.0	0.0	0.0	0.0	21.6	99.9	37
	19.7	4.0	2.7	17.3	56.7	100.4	40.5	0.0	0.0	0.0	0.0	2.7	2.7	2.7	0.0	0.0	0.0	48.6	0.0	2.7	10.8	5.4	18.9	18.9	0.0	13.5	0.0	0.0	32.4	99.9	37
							35.3	0.0	2.9	0.0	0.0	5.9	0.0	0.0	2.9	2.9	0.0	50.0	0.0	2.9	23.5	8.8	35.3	14.7	0.0	0.0	0.0	0.0	14.7	99.8	34
Lower Till							44.1	5.9	5.9	0.0	2.9	0.0	2.9	0.0	0.0	0.0	0.0	61.8	5.9	2.9	11.8	2.9	23.5	14.7	0.0	0.0	0.0	0.0	14.7	99.9	34
	18.7	4.0	2.0	26.7	48.7	100.1	36.7	10.2	0.0	0.0	0.0	4.1	0.0	2.0	2.0	2.0	0.0	57.1	4.1	6.1	10.2	2.0	22.4	20.4	0.0	0.0	0.0	0.0	20.4	99.8	49
							28.6	22.9	0.0	0.0	14.3	5.7	2.9	0.0	0.0	5.7	0.0	80.0	0.0	0.0	5.7	0.0	5.7	11.4	2.9	0.0	0.0	0.0	14.3	100.1	35
	22.3	1.7	1.0	25.3	49.7	100.0	53.1	18.8	0.0	0.0	3.1	3.1	0.0	0.0	0.0	0.0	3.1	81.3	3.1	0.0	9.4	0.0	12.5	6.3	0.0	0.0	0.0	0.0	6.3	100.0	32
	15.3	1.0	1.7	27.7	54.3	100.0	27.0	16.2	0.0	0.0	8.1	0.0	0.0	0.0	2.7	8.1	0.0	62.2	2.7	0.0	8.1	2.7	13.5	16.2	2.7	2.7	0.0	2.7	24.3	99.9	37
	33.4	4.4	0.0	20.1	42.0	99.9	35.9	19.2	0.0	0.0	5.1	1.3	0.0	0.0	2.6	2.6	0.0	66.7	0.0	5.1	0.0	3.8	9.0	24.4	0.0	0.0	0.0	0.0	24.4	100.0	78
							50.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	7.5	2.5	0.0	62.5	0.0	5.0	7.5	5.0	17.5	20.0	0.0	0.0	0.0	0.0	20.0	100.0	40
	19.7	4.3	3.3	22.3	50.3	99.9																									



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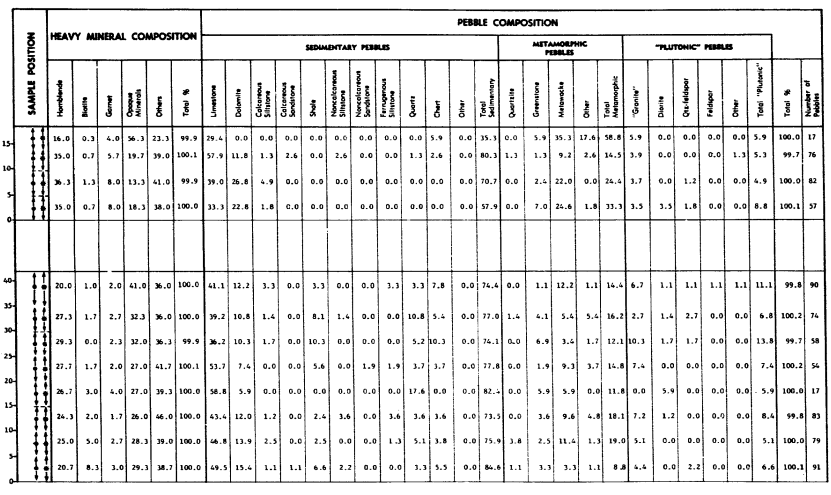
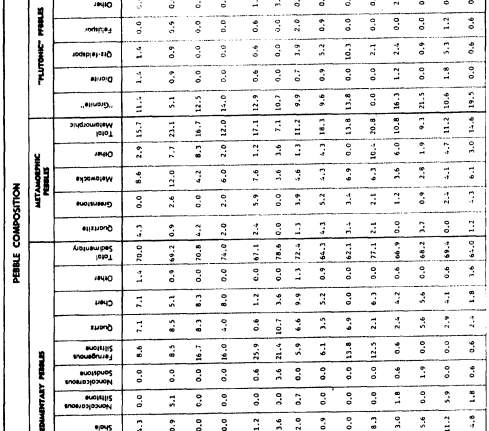


| SAMPLE POSITION | HEAVY MINERAL COMPOSITION | | | | | | | PEBBLE COMPOSITION | | | | | | |

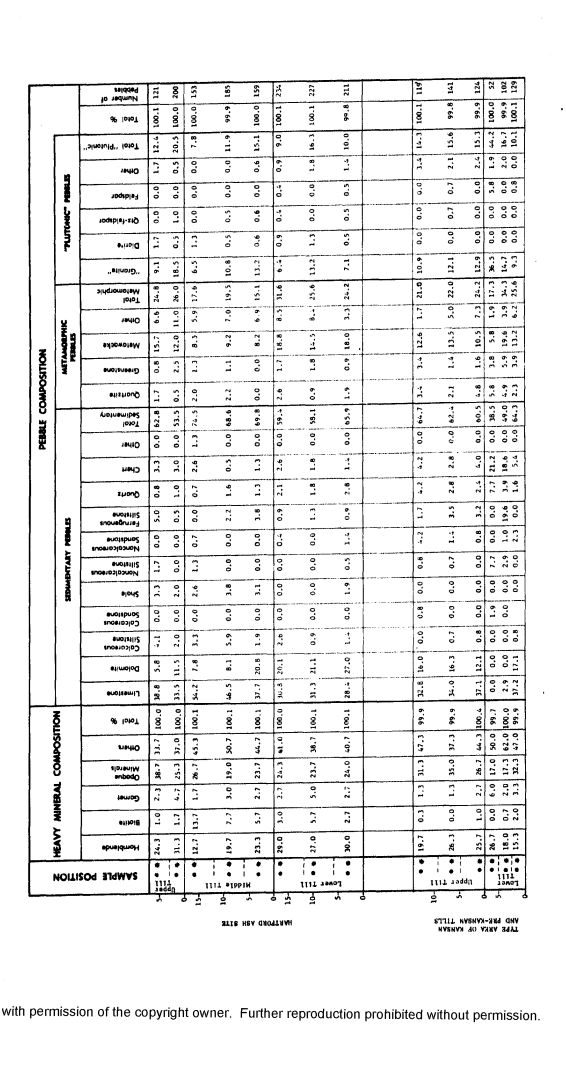


COUNTY LINE SECTION, IOWA

HARRISON COUNTY, IOWA

TYPE LOCALITY OF HERRANAN TILL

| SAMPLE POSITION | HEAVY MINERAL COMPOSITION | | | | | | | PEBBLE COMPOSITION | | | | | | |



APPENDIX H - PROCEDURES

H-1 Grain-size analysis procedure

1. Air dry field sample
2. Disaggregate and pass over #5 (4 mm) sieve (U. S. Standard sieve numbers)
3. Split out 50 g. of minus #5 for silty and clayey soils - 100 gr. of minus #5 for sandy soils
4. Split out 10-15 g. of minus #5 sample for hygroscopic moisture sample and oven-dry at 110° C.
5. Soak for 18 hours or more in 100 mls. of .01 N. sodium oxalate (.67g $Na_2C_2O_4$/liter distilled water).
6. Disperse in dispersion cup and mechanical stirrer for 1 min. Fill dispersion cup at least 1/2 full with sodium oxalate solution.
7. Place slurry in sedimentation cylinder - bring volume up to 1000 ml. with $Na_2C_2)_4$ solution.
8. Agitate for 1 minute (using perforated plunger)
9. Take hydrometer readings at 2, 5, 15, 30, 60, 120, 240 minutes. [1]
   a. Insert hydrometer 20 seconds prior to reading
   b. Clean hydrometer in distilled water after each reading
   c. Take temperature after each reading.
10. Remove sample of suspension from upper 10 cm of hydrometer jar after the 240 minute reading and save for minus 2 micron clay analysis.
11. Wet sieve over #230 and dry plus #230 residue.
12. Dry sieve the plus #230 residue into the #10, #18, #35, #60, #120, and #230 sieves fractions. Record the weight retained on each sieve. Same the plus #230 minus #120 sieve fraction for mineralogical analysis.

[1] Hydrometer No. 152H - read at top of meniscus.

H-2 Clay Mineral Analysis Procedure

Samples of minus 2 micron clay were obtained during textural analysis from the upper 10 cm in the hydrometer jar after 240 minute reading. The procedure used in the clay mineral analysis is slightly modified after that of Jackson, 1956.

(1) Thoroughly shake the 5 to 10 ml. suspension of -2 micron material saved from the textural analysis and pour it into a 90 ml. centrifuge tube and centrifuge for 5 minutes.

(2) Pour off supernatant liquid and add 20 ml. of distilled water. Add 10 ml. of 1 N NaOAc buffer (plt. 5). Set the centrifuge tube and contents into hot water bath and boil gently for 5 minutes.

(3) Add 2.2 ml. of 10 N $MgCl_2$ to the solution in the tube to make the latter approximately 1 N. Centrifuge at 1000 rpm for 3 minutes and decant supernatant liquid.

(4) Add 1 N $MgCl_2$ to the tube, stir, centrifuge at 1000 rpm for 3 minutes and decant.

(5) Wash twice with 1 N Mg $(OAc)_2$ at pH 7. Centrifuge at 1000 rpm for 3 minutes after each washing and decant.

(6) Wash once with 1 N $MgCl_2$, centrifuge at 1000 rpm for 3 minutes and decant.

(7) Wash four times with 80% ethanol. Centrifuge at 1000 rpm for 3 minutes after each washing and decant.

(8) Wash once with 20 ml. of distilled H_2O, centrifuge at 2200 rpm for 10 minutes and decant.

(9) Add 2 ml. of distilled H_2O to the mineral material in the centrifuge tube. Shake and stir until all particles are in suspension.

(10) Wash clean glass slides with acetone and place 4 strips of masking tape about 1/16" wide on the edges of the slide. Mark the glass slide with a diamond pencil. Make 2 slides for each sample.

(11) Place the glass slides on a level surface, stir the suspension in the centrifuge tube again and using a small pipette add several drops of the suspension to the area outlined by masking tape on the slides. Bring the suspension into contact with the masking tape at all points.

(12) Do not move the slides after the suspension has been added until the slides are dry. Allow the slides to air dry under a loose-fitting cover. As soon as the slides are dry carefully peel the masking tape away from the mineral material. The layer of dried mineral material should be about the thickness of cigarette paper.

(13) X-ray one air dried slide per sample through 36° of 2θ.

(14) Add three or four drops of 10% glycerol - 90% ethanol solution to the air dried mineral material on the second slide for each sample. Cover the glycolated

slides and allow them to dry from 2 hours to overnight. X-ray through 18° of 2θ.

(15) After X-raying the air dried slide, heat it to 500° C and hold that temperature for 2 hours. Allow the oven to cool. Remove the slides and place them in a desiccator. X-ray through 18° of 2θ as soon as possible.

H-3 Heavy Mineral Analysis Procedure

1. Weigh a 1-2cc sample of the 0.062 - 0.125 mm sand fraction to nearest .001 gram. (Weighing the sample is necessary only if the percent heavies in the very fine sand fraction is to be determined.)
2. Place the sand in a conical centrifuge tube (40 ml capacity) and add approximately 10 ml of Bromoform (Sp Gr. 2.85). Agitate tube so that the grains are dispersed and let stand about 10 minutes.
3. Add another 5-10 ml.of bromoform using a wash bottle. Direct the bromoform stream on the "cake" so as to thoroughly disperse it. Let stand another 10 minutes.
4. Repeat above step two more times and let stand for several hours.
5. Freeze lower 1/3 of tube in a dry ice and acetone mixture.
6. Pour the light minerals off onto a filter paper. Rinse the tube with jet of bromoform from a wash bottle. Place tube in stand and allow frozen bromoform containing the heavy minerals to thaw.
7. Transfer the filter paper containing the "light" to another funnel and rise with acetone. Allow to air dry and save for "light" mineral analysis.
8. Pour thawed contents of centrifuge tube onto another filter paper. Follow step 6 and 7 above.
9. Weigh heavies to nearest .001 gram and calculate percent heavies in very fine sand fraction. (optional)
10. Mount a representative sample of the heavies on a glass slide and classify 300 grains.

Appendix H-4 Light Mineral Analysis Procedure

1. Weigh the oven-dried "light" mineral fraction of the 0.062 - 0.125 mm sand to the nearest 0.01 gr. Place in beaker and digest the 1:1 HCl for several hours.

2. Wash contents onto a previously dried and weighed filter paper, wash four times with hot distilled water, oven dry at 110° C for several hours, cool and reweigh.

3. Split out about 1/2 gram of the residue and etch in 48 percent hydrofluoric acid for about 30 seconds. Use a lead crucible.

   Immediately dilute acid with distilled water and decant liquid. From this point on, the grains may be treated in a glass vessel.

4. Disperse the sample over the bottom of a beaker and soak in a concentrated solution of sodium colantinitrite (1 gm. sodium cobaltinitrite/4 ml distilled water) for one minute.

5. Wash the sample free of the solution with distilled water and decant the liquid. This will take several washings and decantations.

6. Add 10 drops of hematein solution followed by 5 drops of buffer solution to the sodium cobaltinitrite treated sample and swirl for 2 to 3 minutes. Allow solution to remain in contact with the grains for 5 minutes.

   Hematein solution - Dissolve 0.05 gm of hematein in 100 ml of 95% ethanol.

   Buffer solution - Dissolve 20 gm of sodium acetate ($NaC_2H_3)2.3H_20$) in 100 ml. of distilled water. Add 6 ml. glacial acetic acid and dilute the whole to 200 ml. with distilled water. This solution is about 0.5 N in acidity, and is buffered at pH 4.8.

7. Decant liquid and rinse sample with 95 percent ethanol.

8. Wash twice with acetone and dry.

9. Mount several hundred grains and count 300 using reflected light. Potash feldspar will be yellow, plagioclase feldspars will be various shades of purple with the depth of color increasing from light purple in albite to deep purple in anorthite. Quartz will remain white--usually transparent.

APPENDIX I

Secondary Heavy Mineral and Pebble Count Data

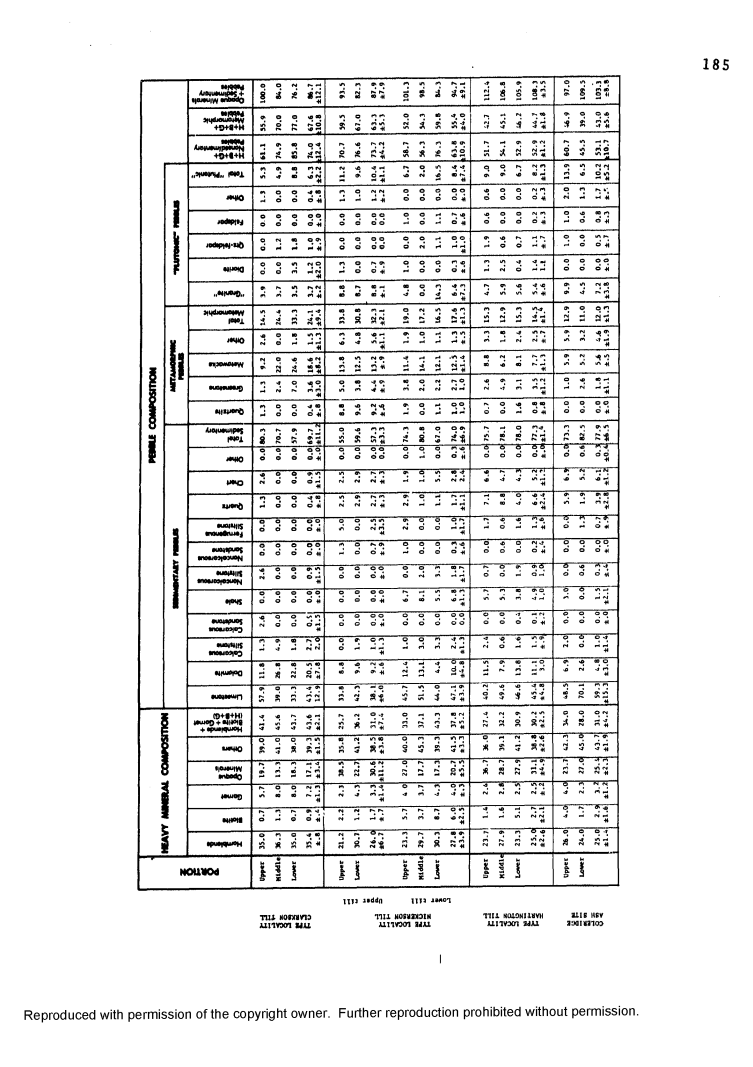
| | | |

CITY WIDE ROCK QUARRY - SECTION 2

TYPE LOCALITY
CEDAR BLUFFS TILL

RIX CREEK
ASH SITE

| PORTION | | HEAVY MINERAL COMPOSITION | | |



| POSITION | | | HEAVY MINERAL COMPOSITION | | |

APPENDIX J

Factor Analysis

BMDX72 Q-MODE FACTOR ANALYSIS - REVISED APRIL 25, 1969
HEALTH SCIENCES COMPUTING FACILITY, UCLA

PROBLEM CODE	TPHCOR
NUMBER OF VARIABLES	27
NUMBER OF SAMPLES	28
INPUT TAPE	5
MAX. ITERATIONS FOR COMMUNALITIES	1
MAX. ITERATIONS FOR ROTATION	50
NUMBER OF FACTORS TO BE ROTATED	2
CONSTANT	0.500000
UPPER LIMIT ON CORRELATION COEFFICIENT	.95000
INPUT FORMAT	(14F5.0/14F5.0)

THE CORRELATION MATRIX IS FORMED
DIAGONAL ELEMENTS ARE UNALTERED
VARIMAX ROTATION IS PERFORMED

DATA - Sample numbers correspond to point numbers in Fig.2-7. Data symbols follow same sequence as data presented in Appendix I except for calcareous sandstone was included with "other" sedimentary pebbles during the factor analysis.

SAMPLE	HORN.	BIO.	GAR.	OPQ	OHVS	OMS	DOL
1	28.0	2.1	5.1	22.7	42.2	35.0	1.5
2	19.9	1.6	3.8	33.2	41.7	41.7	3.8
3	7.1	1.3	1.1	59.7	30.8	50.3	0.0
4	27.0	1.9	5.3	21.7	44.2	33.8	1.8
5	19.2	3.0	3.4	33.0	42.0	40.6	1.6
6	10.3	1.3	2.8	54.9	30.7	49.2	0.2
7	24.1	5.2	3.1	24.3	43.3	34.3	13.2
8	26.0	1.7	3.3	30.6	38.5	38.1	9.2
9	27.8	6.0	4.0	20.7	41.5	47.1	10.0
10	35.4	0.9	7.2	17.1	39.3	43.4	20.5
11	25.0	2.7	2.5	31.1	38.8	45.4	11.1
12	25.0	2.9	3.2	25.4	43.7	59.3	4.8
13	25.4	1.8	4.0	24.8	44.0	43.2	12.4
14	20.7	3.8	2.5	31.7	41.3	40.8	4.9
15	27.1	4.2	4.1	22.3	42.4	36.1	0.0
16	21.2	3.2	2.0	24.7	48.8	39.9	12.7
17	7.4	1.4	1.8	41.4	47.9	80.1	6.2
18	23.9	0.4	1.8	31.0	43.0	34.6	14.8
19	15.3	2.0	3.3	32.3	47.0	37.2	17.1
20	14.2	0.4	1.6	23.5	60.3	28.6	14.4
21	27.8	1.4	3.5	32.0	35.4	36.2	8.7
22	18.6	9.0	2.5	23.1	46.9	46.1	12.2
23	28.7	3.8	3.5	24.0	40.1	30.2	22.7
24	9.5	0.6	2.0	26.4	61.9	77.6	1.7
25	17.0	4.7	2.2	40.5	35.7	38.9	12.5
26	22.9	1.4	3.7	16.2	56.0	43.4	9.4
27	27.7	2.3	3.7	24.7	41.7	39.5	7.4
28	28.2	1.1	5.0	25.1	40.6	44.4	9.4

SAMPLE	CSLT	SH	SLT	SS	FSLT	Q	CH
1	2.6	0.2	1.4	0.9	2.8	5.5	4.6
2	2.9	0.0	1.4	1.0	3.5	6.2	5.0
3	4.1	0.0	3.1	6.9	10.1	5.2	13.1
4	4.3	0.0	0.6	0.0	2.1	7.5	4.2
5	1.8	0.1	1.8	0.2	3.2	9.1	8.7
6	2.4	0.2	4.0	1.9	11.9	9.4	8.4
7	1.4	4.8	1.1	0.4	2.4	4.6	4.4
8	1.0	0.0	0.0	0.7	2.5	2.7	2.7
9	2.4	6.8	1.8	0.3	0.9	1.7	2.8
10	2.7	0.0	0.9	0.0	0.0	0.4	0.8
11	1.5	4.9	0.9	0.2	1.3	6.6	5.2
12	1.0	1.5	0.3	0.0	0.7	3.9	6.1
13	2.5	0.2	0.3	0.8	2.1	1.7	4.7
14	7.8	5.8	1.0	0.0	5.8	1.9	3.9
15	0.3	0.0	8.7	0.3	3.5	3.8	1.2
16	1.0	4.2	1.9	0.8	0.3	2.3	2.7
17	2.3	1.9	0.9	0.1	0.1	2.1	1.8
18	0.5	0.0	0.5	2.1	2.8	3.1	3.7
19	0.8	0.0	0.0	2.3	0.0	1.6	5.4
20	0.8	3.1	1.1	0.5	9.9	5.2	5.2
21	3.1	2.7	0.9	0.0	2.8	0.9	3.2
22	3.7	3.2	0.4	0.2	2.0	1.2	1.5
23	1.6	0.6	0.2	0.6	1.0	2.2	1.9
24	6.5	0.5	2.8	0.0	0.4	1.1	5.1
25	1.2	0.7	0.7	1.0	2.8	1.9	4.9
26	0.3	0.0	3.1	0.3	0.8	4.7	6.6
27	0.0	0.8	0.3	0.0	2.8	5.1	4.1
28	3.4	1.5	1.0	0.3	2.2	2.0	3.9

SAMPLE	OS	TS	QZT	GNST	W	MO	TM
1	0.7	55.2	8.8	5.3	10.9	5.9	30.8
2	0.9	66.2	2.6	1.3	8.5	7.3	19.5
3	0.5	93.2	1.4	0.2	1.0	0.3	2.9
4	1.6	55.8	7.8	4.6	13.0	7.0	32.0
5	0.4	67.8	1.7	2.8	7.8	4.7	17.0
6	0.0	88.6	0.2	0.5	0.8	0.7	2.3
7	0.6	67.1	1.6	2.7	11.4	5.1	20.8
8	0.0	57.3	9.2	4.4	13.2	5.6	32.3
9	0.3	74.0	1.0	2.7	12.5	1.3	17.6
10	0.9	69.6	0.4	3.6	18.6	1.5	24.1
11	0.1	77.3	0.8	3.5	7.7	2.5	14.5
12	0.3	77.9	0.0	1.8	5.6	4.6	12.0
13	1.1	69.0	3.4	1.3	11.5	6.5	22.7
14	1.0	71.8	1.9	0.0	11.7	3.9	17.5
15	0.0	53.9	0.3	4.8	17.0	5.3	27.3
16	0.3	66.2	2.3	3.2	7.5	2.6	15.6
17	0.2	95.6	0.5	0.0	1.3	0.8	2.5
18	0.3	62.5	3.4	2.1	12.2	4.7	22.4
19	0.0	64.3	2.3	3.9	13.2	6.2	25.6
20	0.8	69.7	2.2	2.3	5.9	4.2	14.6

SAMPLE	OS	TS	QZT	GNST	W	MO	TM
21	0.0	58.2	1.1	1.7	13.9	8.8	25.4
22	0.4	71.0	1.4	0.8	8.6	6.6	17.4
23	0.0	61.1	1.8	1.5	17.1	6.7	27.1
24	0.0	95.6	0.4	0.0	2.2	1.2	3.0
25	0.0	64.5	3.4	1.4	8.2	8.8	21.8
26	0.0	68.3	1.1	0.9	13.2	4.6	19.6
27	0.3	60.2	2.2	2.7	14.3	4.2	23.4
28	0.0	68.0	1.6	4.8	9.0	5.3	20.6

SAMPLE	G	DI	QF	F	DP	TP
1	11.4	0.9	0.8	0.4	0.6	14.0
2	11.2	0.4	0.9	1.1	0.7	14.2
3	3.4	0.0	0.2	0.5	0.0	4.0
4	8.4	0.2	2.7	0.4	0.6	12.3
5	9.6	0.1	3.3	1.1	1.2	15.3
6	4.4	0.1	2.3	2.3	0.0	9.1
7	9.1	0.4	1.9	0.0	0.9	12.1
8	8.8	0.7	0.0	0.0	1.2	10.4
9	6.4	0.3	1.0	0.7	0.0	8.4
10	3.7	1.2	1.0	0.0	0.4	6.3
11	5.4	1.4	1.1	0.2	0.2	8.2
12	7.2	0.0	0.5	0.8	1.7	10.2
13	5.5	0.5	0.8	0.3	1.2	8.3
14	9.7	0.0	0.0	1.0	0.0	10.7
15	15.5	0.0	2.1	0.3	0.9	18.8
16	17.0	0.6	0.3	0.0	0.3	18.2
17	1.4	0.1	0.2	0.2	0.0	1.9
18	12.0	0.0	0.2	0.2	2.6	15.1
19	9.3	0.0	0.0	0.8	0.0	10.1
20	11.9	0.5	2.3	0.4	0.6	15.8
21	13.8	1.1	0.5	0.0	1.1	16.5
22	10.2	0.8	0.4	0.0	0.2	11.6
23	8.9	0.9	0.3	0.3	1.4	11.8
24	1.2	0.0	0.0	0.6	0.0	1.4
25	11.2	0.0	1.4	0.0	1.2	13.7
26	8.9	0.6	0.8	0.8	1.2	12.2
27	14.1	0.0	0.9	0.3	1.2	16.4
28	10.2	0.9	0.0	0.3	0.0	11.4

SAMPLE	MEAN	ST. DEV.	SAMPLE	MEAN	ST. DEV.
1	11.122210	14.741146	15	11.118503	14.836321
2	11.129620	16.381607	16	11.103687	16.687576
3	11.496273	22.248734	17	11.114778	25.083267
4	11.140731	14.867089	18	11.107389	15.786507
5	11.129621	16.459000	19	11.111093	16.518021
6	11.070346	21.012070	20	11.111094	17.298538
7	11.122206	15.812861	21	11.137026	15.077384
8	11.114800	15.386150	22	11.111093	17.367523
9	11.111094	17.642456	23	11.111097	15.408451
10	11.107387	17.505341	24	11.174034	25.201355
11	11.114799	17.998917	25	11.122208	16.063812
12	11.125913	19.493500	26	11.148134	17.659683
13	11.111094	16.990143	27	11.122208	15.612706
14	11.151834	16.945923	28	11.118504	16.731613

CORRELATION MATRIX

	1	2	3	4	5
1	1.00000				
2	0.96247	1.00000			
3	0.81434	0.92326	1.00000		
4	0.99632	0.95702	0.80268	1.00000	
5	0.95222	0.99557	0.93171	0.94772	1.00000
6	0.81228	0.92844	0.99347	0.80191	0.93876
7	0.96075	0.97719	0.87535	0.96050	0.97238
8	0.98371	0.96646	0.84796	0.97975	0.95049
9	0.94362	0.96526	0.88311	0.94097	0.96099
10	0.93249	0.92421	0.81202	0.93474	0.91088
11	0.93012	0.97881	0.93674	0.92600	0.97889
12	0.92805	0.97447	0.91404	0.92109	0.97390
13	0.96496	0.97975	0.88287	0.96517	0.97030
14	0.94656	0.98875	0.92896	0.94327	0.98378
15	0.97797	0.95323	0.79552	0.97195	0.94430
16	0.94798	0.97494	0.86300	0.93914	0.96948
17	0.84294	0.93801	0.93982	0.83682	0.93868
18	0.96402	0.98063	0.87605	0.95903	0.97030
19	0.94801	0.97282	0.87102	0.94870	0.96192
20	0.91004	0.94187	0.83485	0.91176	0.94232
21	0.96905	0.97652	0.86741	0.96089	0.96158
22	0.94130	0.97679	0.88106	0.93872	0.96938
23	0.94407	0.93583	0.80420	0.94616	0.91930
24	0.86356	0.93592	0.90042	0.86231	0.93835
25	0.93246	0.98336	0.92774	0.92430	0.97399
26	0.95692	0.96256	0.82837	0.95932	0.95923
27	0.98244	0.98037	0.85206	0.97632	0.97225
28	0.96829	0.98384	0.89006	0.96204	0.97537

CORRELATION MATRIX (Cont'd.):

	6	7	8	9	10
6	1.00000				
7	0.87661	1.00000			
8	0.84227	0.96562	1.00000		
9	0.88158	0.98386	0.94823	1.00000	
10	0.80379	0.96509	0.94763	0.97493	1.00000
11	0.93597	0.98108	0.94599	0.98664	0.95243
12	0.91694	0.96188	0.92968	0.98356	0.93866
13	0.87982	0.99042	0.97536	0.98734	0.97581
14	0.92986	0.98123	0.95494	0.97904	0.93603
15	0.80210	0.95056	0.95748	0.93623	0.92007
16	0.87110	0.98379	0.94433	0.96911	0.93424
17	0.94824	0.90343	0.86853	0.93489	0.86746
18	0.87596	0.98814	0.97841	0.96080	0.95101
19	0.97241	0.98035	0.97110	0.95282	0.93995
20	0.84868	0.96142	0.89951	0.92274	0.88596
21	0.86453	0.97190	0.98113	0.95293	0.94268
22	0.88754	0.98528	0.94684	0.98516	0.94884
23	0.79901	0.97752	0.96514	0.94987	0.97401
24	0.90909	0.91384	0.86574	0.94531	0.88000
25	0.92924	0.96508	0.96402	0.94247	0.90972
26	0.83431	0.97937	0.94230	0.97290	0.95227
27	0.85470	0.98347	0.97834	0.97135	0.95699
28	0.88825	0.98695	0.97175	0.98911	0.97074

	11	12	13	14	15
11	1.00000				
12	0.98445	1.00000			
13	0.98240	0.97551	1.00000		
14	0.98476	0.97317	0.98050	1.00000	
15	0.91432	0.91909	0.94572	0.93826	1.00000
16	0.96577	0.96281	0.97219	0.97114	0.94936
17	0.95484	0.96932	0.92527	0.94179	0.83171
18	0.96696	0.94622	0.98292	0.97270	0.95465
19	0.95941	0.93882	0.97991	0.96605	0.93319
20	0.92754	0.91203	0.94074	0.94137	0.90186
21	0.95441	0.93893	0.97081	0.96884	0.96723
22	0.97774	0.97993	0.98584	0.98172	0.93545
23	0.93979	0.90768	0.97116	0.93820	0.93267
24	0.94765	0.97414	0.93519	0.94229	0.85277
25	0.96735	0.94575	0.96496	0.97357	0.92019
26	0.95497	0.96323	0.98081	0.95862	0.95319
27	0.96232	0.95941	0.98152	0.97036	0.98142
28	0.98534	0.98240	0.99341	0.98262	0.95598

	16	17	18	19	20
16	1.00000				
17	0.91230	1.00000			
18	0.98113	0.89038	1.00000		
19	0.96986	0.90449	0.98756	1.00000	
20	0.96830	0.86911	0.95355	0.95239	1.00000

	16	17	18	19	20
21	0.96039	0.87163	0.98467	0.96479	0.90660
22	0.98475	0.94438	0.96992	0.97179	0.95288
23	0.94896	0.83088	0.97929	0.96937	0.91976
24	0.92555	0.98512	0.89035	0.90549	0.89915
25	0.95709	0.92386	0.97873	0.97751	0.91880
26	0.97783	0.90140	0.96521	0.96309	0.96214
27	0.97892	0.88537	0.98659	0.96719	0.93332
28	0.97838	0.92646	0.98058	0.96826	0.93153

	21	22	23	24	25
21	1.00000				
22	0.95352	1.00000			
23	0.96616	0.94809	1.00000		
24	0.86400	0.95591	0.83671	1.00000	
25	0.97478	0.96125	0.94178	0.89919	1.00000
26	0.94042	0.97923	0.94765	0.93694	0.92456
27	0.98659	0.97002	0.96603	0.89531	0.95849
28	0.97841	0.98331	0.96071	0.93291	0.96458

	26	27	28
26	1.00000		
27	0.97481	1.00000	
28	0.97416	0.98756	1.00000

	Eigenvalues	Cumulative Proportion of Total Variance	Sample	Estimated Communality	Final Communality
1	26.42990	0.94393	1	1.000000	0.970880
2	0.72884	0.96995	2	1.000000	0.988695
3	0.26961	0.97958	3	1.000000	0.961653
4	0.17519	0.98584	4	1.000000	0.969040
5	0.16390	0.99169	5	1.000000	0.981567
6	0.07111	0.99423	6	1.000000	0.972203
7	0.06015	0.99638	7	1.000000	0.988798
8	0.02367	0.99723	8	1.000000	0.967987
9	0.02238	0.99803	9	1.000000	0.971574
10	0.01417	0.99853	10	1.000000	0.936564
11	0.01219	0.99897	11	1.000000	0.986922
12	0.00757	0.99924	12	1.000001	0.974881
13	0.00649	0.99947	13	1.000000	0.990478
14	0.00504	0.99965	14	1.000000	0.986715
15	0.00348	0.99977	15	1.000000	0.953911
16	0.00252	0.99986	16	1.000000	0.969921
17	0.00118	0.99990	17	1.000000	0.973101
18	0.00103	0.99994	18	1.000000	0.983949
19	0.00069	0.99996	19	1.000000	0.966835
20	0.00046	0.99998	20	1.000000	0.904551
21	0.00021	0.99999	21	1.000000	0.968621
22	0.00007	0.99999	22	1.000000	0.978526
23	0.00006	0.99999	23	1.000000	0.964881
24	0.00002	0.99999	24	1.000000	0.940096
25	0.00001	0.99999	25	1.000000	0.960219
26	0.00000	0.99999	26	1.000000	0.965328
27	0.00000	0.99999	27	1.000000	0.990350
28	0.00001	0.99999	28	1.000000	0.990494

FACTOR MATRIX BEFORE ROTATION

SAMPLE	FACTOR 1	FACTOR 2
1	0.96660	-0.19124
2	0.99337	0.04372
3	0.90653	0.37398
4	0.96286	-0.20479
5	0.98761	0.07869
6	0.90831	0.38364
7	0.99235	-0.06358
8	0.97368	-0.14119
9	0.98567	0.00453
10	0.95794	-o.13755
11	0.98829	0.10103
12	0.98067	0.11476
13	0.99440	-0.04045
14	0.99113	0.06616
15	0.95631	-0.19845
16	0.98419	-0.03587
17	0.93655	0.30981
18	0.98841	-0.08362
19	0.98183	-0.05341
20	0.95061	-0.02993
21	0.97835	-0.10701
22	0.98904	0.01817
23	0.96091	-0.20379
24	0.94063	0.23520
25	0.97813	0.05901
26	0.97855	-0.08815
27	0.98769	-0.12169
28	0.99484	-0.02808

ORTHOGONAL ROTATION

ITERATION	SIMPLICITY CRITERION
0	-0.090787
1	-1·313378
2	-1.313378

ROTATED FACTOR MATRIX (These results are shown graphically in Figure 2-8)

Sample	1	2
1	0.86068	0.47970
2	0.72905	0.67615
3	0.44913	0.87174
4	0.86661	0.46694
5	0.70203	0.69908
6	0.44424	0.88026
7	0.79771	0.59368
8	0.83370	0.52243
9	0.74854	0.64129
10	0.81934	0.51502
11	0.68809	0.71655
12	0.67340	0.72209
13	0.79431	0.61265
14	0.71282	0.69181
15	0.85751	0.46754
16	0.77356	0.60953
17	0.51354	0.84225
18	0.80767	0.57586
19	0.78310	0.59463
20	0.74411	0.59233
21	0.81514	0.55152
22	0.74228	0.65387
23	0.86447	0.46645
24	0.56493	0.78800
25	0.70754	0.67794
26	0.80309	0.56602
27	0.83176	0.54637
28	0.77664	0.62236

FACTOR SCORE COEFFICIENTS

SAMPLE	FACTOR 1	FACTOR 2
1	0.0	0.0
2	0.0	0.0
3	-0.28865	0.41965
4	0.31079	-0.24316
5	-0.01953	0.11719
6	-0.29297	0.42578
7	0.06641	0.00781
8	0.27734	-0.24609
9	0.02344	0.0
10	0.14453	-0.15918
11	-0.11328	0.09766
12	-0.07422	0.20313
13	0.0	0.0
14	-0.00781	0.10938
15	0.18725	-0.17374
16	0.09766	-0.00391
17	-0.22266	0.42578
18	0.13281	-0.15234
19	0.03516	-0.02344
20	0.03760	0.02612
21	0.10938	-0.05469
22	0.11328	-0.02344
23	0.09766	-0.04297
24	-0.30469	0.33594
25	-0.05469	0.06250
26	0.26172	-0.16797
27	0.06152	-0.06177
28	0.17578	-0.09375

FACTOR SCORES

VARIABLE		
1	1.77832	-1.05229
2	-0.55860	-0.14097
3	-0.38781	-0.30102
4	-0 26889	1.99651
5	2.45168	0.25346
6	0.62440	2.34038
7	0.27180	-0.60995
8	-0.73195	0.02042
9	-0.72046	-0.05156
10	-0.70380	-0.09778
11	-0.83900	-0.02354
12	-0.82931	0.19487
13	-0.61011	0.01974
14	-0.77607	0.27051
15	-0.73408	-0.16808
16	1.93041	3.31150
17	-0.36038	-0.42352
18	-0.39140	-0.39316
19	0.79025	-1.06468
20	-0.16603	-0.42778
21	2.19572	-1.83835
22	0.34637	-0.57446
23	-0.71730	-0.18720
24	-0.69818	-0.15223
25	-0.79495	-0.08902
26	-0.67174	-0.21564
27	0.57112	-0.59614

VITA

John David Boellstorff was born on May 14, 1940, on a farm near Johnson, Nebraska. Following graduation from Johnson High School in 1958 he entered the University of Nebraska at Lincoln, and received the degree Bachelor of Science in Geology. He continued graduate studies in geology at the University of Nebraska until 1964 when he was employed by Western Laboratories, an engineering consulting firm in Lincoln, Nebraska. In 1965 he was employed by the Conservation and Survey Division of the University of Nebraska at Lincoln and continued his graduate studies in geology, receiving the degree Masters of Science in 1968.

In September, 1968, he entered the Graduate School at Louisiana State University in Baton Rouge to further pursue graduate studies in geology. Having passed his preliminary requirements for the Ph.D. degree in Geology in June, 1971, he returned to employment with the Conservation and Survey Division at the University of Nebraska at Lincoln and pursued his thesis research work (in absentia).

EXAMINATION AND THESIS REPORT

Candidate: John David Boellstorff

Major Field: Geology

Title of Thesis: Tephrochronology, Petrology, and Stratigraphy of some Pleistocene Deposits of the Central Plains U.S.A.

Approved:

C. O. Dunham
Major Professor and Chairman

James B. Trayhorn
Dean of the Graduate School

EXAMINING COMMITTEE:

Edgar A. Steele

Ray E. Ferrell Jr.

Richard Moore Jr.

Micah C. Foley

James P. Morgan

Date of Examination:

November 6, 1973